Improving Routing Performance of Multipath Ad Hoc On-demand Distance Vector in Mobile Ad Hoc Networks

by

Ammar Thabit Zahary

School of Computing, Faculty of Computing
Sciences and Engineering, De Montfort University, UK

Dissertation submitted in partial fulfillment
of the requirements for the degree of

Doctor of Philosophy

in Data Communication and Networking

June, 2008

Abstract

The aim of this research is to improve routing fault tolerance in Mobile Ad hoc Networks (MANETs) by optimising multipath routing in a well-studied reactive and single path routing protocol known as Ad hoc On-demand Distance Vector (AODV). The research also aims to prove the effect of varying waiting time of Route Reply (RREP) procedure and utilising the concept of *efficient routes* on the performance of multipath extensions to AODV. Two novel multipath routing approaches are developed in this thesis as new extensions to AODV to optimise routing overhead by improving Route Discovery Process (RDP) and Route Maintenance Process (RMP) of multipath AODV. The first approach is a link-disjoint multipath extension called "Threshold efficient Routes in multipath AODV" (TRAODV) that optimises routing packets overhead by improving the RDP of AODV which is achieved by detecting the waiting time required for RREP procedure to receive a *threshold* number of *efficient routes*. The second approach is also a link-disjoint multipath extension called "On-demand Route maintenance in Multipath AoDv" (ORMAD) which is an extension to TRAODV that optimises routing packets and delay overhead by improving the RMP of TRAODV. ORMAD applies the concepts of *threshold waiting time* and *efficient routes* to both phases RDP and RMP. It also applies RMP only to efficient routes which are selected in the RDP and when a route fails, it invokes a local repair procedure between upstream and downstream nodes of the broken link. This mechanism produces a set of alternative subroutes with less number of hops which enhances route efficiency and consequently minimises the routing overhead.

TRAODV and ORMAD are implemented and evaluated against two existing multipath extensions to AODV protocol and two traditional multipath protocols. The existing extensions to AODV used in the evaluation are a well-known protocol called Ad hoc On-demand Multipath Distance Vector (AOMDV) and a recent extension called Multiple Route AODV (MRAODV) protocol which is extended in this thesis to the new approach TRAODV while the traditional multipath protocols used in

the evaluation are Dynamic Source Routing (DSR) and Temporally Ordered Routing Algorithm (TORA). Protocols are implemented using NS2 and evaluated under the same simulation environment in terms of four performance metrics; packet delivery fraction, average end-to-end delay, routing packets overhead, and throughput.

Simulation results of TRAODV evaluation show that the average number of routes stored in a routing table of MRAODV protocol is always larger than the average number of routes in TRAODV. Simulation results show that TRAODV reduces the overall routing packets overhead compared to both extensions AOMDV and MRAODV, especially for large network size and high mobility. A vital drawback of TRAODV is that its performance is reduced compared to AOMDV and MRAODV in terms of average end-to-end delay. Additionally, TORA still outperforms TRAODV and the other extensions to AODV in terms of routing packets overhead.

In order to overcome the drawbacks of TRAODV, ORMAD is developed by improving the RDP of TRAODV. The performance of ORMAD is evaluated against RREP waiting time using the idea of utilising the efficient routes in both phases RDP and RMP. Simulation results of ORMAD show that the performance is affected by varying the two RREP waiting times of both RDP and RMP in different scenarios. As shown by the simulation results, applying the short and long waiting times in both phases tends to less performance in terms of routing packets overhead while applying the moderate waiting times tends to better performance. ORMAD enhances routing packets overhead and the average end-to-end delay compared to TRAODV, especially in high mobility scenarios. ORMAD has the closest performance to TORA protocol in terms of routing packets overhead compared to AOMDV and MRAODV.

Relevant concepts are formalised for ORMAD approach and conducted as an analytical model in this thesis involving the whole process of multipath routing in AODV extensions. ORMAD analytical model describes how the two phases RDP and RMP interact with each other with regard to two performance metrics; total number of detected routes and *Route Efficiency.*

Declaration

I declare that the work described in this thesis is original work undertaken by me for the degree of Doctor of Philosophy, at the School of Computing, Faculty of Computing Sciences and Engineering, at De Montfort University, Leicester, United Kingdom.

No part of the material described in this thesis has been submitted for the award of any other degree or qualification in this or any other university or college of advanced education.

This thesis is written by me and produced using LaTeX

Ammar T. Zahary
Leicester, United Kingdom
June, 2008

List of Publications

Published papers:

Ammar Zahary and Aladdin Ayesh, Analytical Study to Detect Threshold Number of Efficient Routes in Multipath AODV Extensions, IEEE Proceeding ICCES'07, 1-4244-1366, IEEE, 2007.

Submitted Papers:

Ammar Zahary and Aladdin Ayesh, An Analytical Review for Multipath Routing in MANETs, Journal Paper, submitted to IJWMC.

Ammar Zahary and Aladdin Ayesh, Simulation-Based Evaluation for Multipath AODV Extensions in Mobile Ad Hoc Networks, Journal Paper, submitted to IJAHUC.

Ammar Zahary and Aladdin Ayesh, On-demand Route Maintenance in Multipath AODV (ORMAD), Conference Paper, submitted to IEEE, ICCES'08, Cairo, Egypt.

Dedication

To my mother and father:

The two uneducated persons who taught me,
for their endless love.

To my family:

Who have supported me while they had to
be extremely patient during the research years.

Acknowledgements

First and foremost, my deepest gratefulness goes to GOD for all his blessings without which nothing of my work would have been done.

I would also like to express my sincere gratitude to my supervisor Dr. Aladdin Ayesh at De Montfort University, Leicester, UK, for his guidance, ideas, valuable directions and support throughout my research study. I am deeply indebted to him for his insights and suggestions to the thesis topic and for valuable supervision at various stages of my work. He has helped me in many ways and has developed my academic thinking, problem solving and technical writing which will be very helpful in my future work and research. Many thanks also to my second superervisor Dr. Amelia Platt for the scientific support I have received from her.

Grateful acknowledgement should be mentioned here to Prof. Hussein Zedan at De Montfort University, Leicester, UK, for his ideas, encouragement and support. His support has greatly inspired me to complete this work in the required duration.

I would also like to thank my sponsor University of Science and Technology (UST) in Yemen, especially Prof. Abdulraqib Asaad, the dean of postgraduate studies and all my colleagues there who supported me in order to complete this thesis.

Special thank to my wife, Asma Al-Shargabi, who inspired me for so many ideas in my reasearch and for her great support. She had to spend a lot of time and a lot of patience to share in problem solutions of the research.

I am grateful for the support and assistance that I have received from all members of IMRCC and STRL research groups in DMU especially, Dr. Mousa Al-Akhras, Dr. Iman Al-Momani and Mr. Omar Al-Dabbas who have made me to feel as a member of their own groups. I have benefited from many discussions and collaboration with them.

I would also like to express my great thanks to the team of itexsolutions company for the assistance that I have received from them during the whole duration of my research. Special thanks to Mr. Lotfi Al-Sarori, Mr. Abdulhakeem N. Khaled, Mr.

Faisal Al-Asbahi and Mr. Ahmed Al-Salehi.

My gratefulness should be also submitted to my students in girls branch, UST, especially the two students Amal Al-Shargabi and Sara Arsalan for their assistance in some parts of the implementation process of the research. Many thanks also to students Asma Al-Sanhani, Hala Abusaleh, Lamis Najeeb, Reem Al-Moflehi and Rofayda Al-Hammadi for the assistance that I have received from them during the research period.

Finally yet importantly, I would like to express my gratefulness to my friends and colleagues Mr. Moussa Barkhadleh, Mr. Abdulaziz Aldobhani, and Mr. Mohammed Alshaddadi who helped me to overcome many troubles in the research, journeys, and the accommodation during the research years.

Ammar T. Zahary

List of Acronyms

2HBR	Two Hops Backup Routing
AEADMRA	Ant-based Energy Aware Disjoint Multipath Routing Algorithm
AGT	Agent-level Trace
AntHocNet	Ant Agents for Hybrid Multipath Routing in MANETs
AODV	Ad hoc On-demand Distance Vector
AODV-BR	AODV Backup Routing
AODVM	AODV Multipath
AODV-MM	AODV with Meshed Multipath
AOMDV	Ad hoc On-demand Multipath Distance Vector
ATM	Asynchronous Transfer Mode
AVGD	Average End-to-End-Delay
BcastID	Broadcast IDentifier
BRAN	Broadband Radio Access Networks
CBR	Constant Bit Rate
CGSR	Cluster-head Gateway Switch Routing
CNR	Connectivity Ratio
DAG	Directed Acyclic Graph
DARPA	Defense Advanced Research Projects Agency
DCLQ	Distributed Cross-Layer QoS
DestID	Destination Identifier
DestSeqNum	Destination Sequence Number
DSDV	Destination Sequence Distance Vector
DSR	Dynamic Source Routing
E	Route Efficiency
ECCA	Energy Collision-Constrained Algorithm
EFR	Efficient Routes
ETSI	European Telecommunications Standardisation Institute
FIFO	First In First Out
FSR	Fisheye State Routing
GPS	Global Positioning System
GRDP	Global Route Discovery Process
GSR	Global State Routing
GUI	Graphical User Interface
GWT	Global Waiting Time
HiperLAN2	High Performance Radio LAN Type 2
HC	Hop Count
HSR	Hierarchical State Routing
IARP	Intrazone Routing Protocol
IEEE	Institute of Electrical and Electronics Engineers
IERP	Interzone Routing Protocol

IETF	Internet Engineering Task Force
IER	Inefficient Routes
IP	Internet Protocol
ISO	International Organization for Standardization
LAN	Local Area Network
LAR	Location-Aided Routing
LRDP	Local Route Discovery Process
LWT	Local Waiting Time
MAC	Medium Access Control
MANET	Mobile Ad hoc Network
MBR	Mobility Ratio
MDG	Multipath Degree
MDTMR	Multiple Disjoint Trees Multicast Routing
MEER	Multipath Energy-Efficient Routing
MLAR	Multipath Location-Aided Routing
MNH	Multiple Next Hops
MP-DSR	Multipath-DSR
MPSR	Multipath Power Sensitive Routing Protocol
MRAODV	Multiple-Route AODV
MTS	Multipath TCP Security
NAM	Network Animator
nCr	Combinations function
NDMR	Node-Disjoint Multipath Routing
NS2	Network Simulator 2
OLSR	Optimised Link-State Routing Protocol
ORMAD	On-demand Route maintenance in Multipath AODV
OSI	Open Systems Interconnection
OTcl	Object Tool Command Language
PDA	Personal Digital Assistant
PDF	Packet Delivery Fraction
PNNI	Private Network-to-Network Interface
QoS	Quality of Service
RDP	Route Discovery Process
RERR	Route Error
RFC	Request For Comments
RMS	Route Miss
RMP	Route Maintenance Process
ROAM	Routing On-demand Acyclic Multipath
RPO	Routing Packets Overhead
RREP	Route Reply

RREQ	Route Request
RTR	Routing Trace level
RUP	Rationale Unified Process
SDMSR	Secure, Disjoint, Multipath Source Routing
SrcID	Source Identifier
SrcSeqNum	Source Sequence Number
SWRR	Selective Weighted Round Robin
TCL	Tool Command Language
TCP	Transmission Control Protocol
TORA	Temporarily Ordered Routing Algorithm
TRAODV	Threshold efficient Routes in multipath AODV
TTL	Time To Live
UC	Use Case
UML	Unified Modeling Language
WLAN	Wireless Local Area Network
WRP	Wireless Routing Protocol
WTR	waiting Time Ratio
ZRP	Zone Routing Protocol
ZHLS	Zone-Based Hierarchical Link State

Contents

List of Tables

List of Figures

Chapter 1

Introduction

1.1 Overview

Mobile Ad hoc Network (MANET) concept is developed recently to convoy the increasing demand on mobile and ubiquitous access to network resources, especially the Internet [1]. Thus, MANET is a key part in the next generation network structure in which the wireless Internet will be involved. A MANET is a collection of mobile nodes that form a dynamic topology and highly resource constrained network [2]. Unlike Wireless LAN (WLAN) which is a single hop and an infrastructure-based network, MANET is considered a multi-hop and infrastructureless network which means that MANETs operate without support of any fixed infrastructure or centralised administration [3].

In MANETs, mobile nodes are arbitrary and dynamically connected to form a network depending on their positions and transmission ranges. A node in MANETs is an autonomous terminal which means that it functions as both a host and a router [4]. Nodes must cooperate to provide connectivity in a multi-hop manner and this is the reason why MANETs are called multi-hop networks [5][6][7].

Routing issue is one of the most challenging and interesting research areas in MANETs [1][2]. Generally, the main function of routing in a network is to detect and maintain the optimal route to send data packets between a source and destination via intermediate node(s). *Multipath* routing concept is a new trend addressed in so many extensions to traditional routing protocols in MANETs. Generally, multipath routing is considered as an advantage due to easy recovery from a route failure, and thus multipath protocols are considered more reliable and robust than single path protocols [9]. In a broad sense, multipath routing enables route reliability and also facilitates load balancing which are commonly used in several applications, especially in routing fault tolerance and Quality of Service (QoS) provisioning for heavy multimedia and real-time traffic. Both single path and multipath routing protocols in MANETs usually consist of two main processes (phases), Route Discovery Process (RDP) and Route Maintenance Process (RMP) [10][11]. Most extensions to traditional routing protocols in MANETs try to optimise either RDP or RMP, or both.

The aim of this thesis is to improve routing fault tolerance in MANETs by optimising multipath routing in a well-studied traditional reactive and single path routing protocol known as Ad hoc On-demand Distance Vector (AODV). [12]. AODV is basically designed as a single path routing protocol even though multiple routes can be detected due to routing discovery. AODV maintains only the optimal route, which has the minimum hop count, and discards the other routes so that some efficient routes are probably lost. The definition of an efficient route is introduced later in Chapter 4.

In this thesis, we develop two novel multipath routing approaches in MANETs as new extensions to the traditional protocol AODV. The first approach is a link-disjoint multipath extension called "Threshold efficient Routes in multipath AODV" (TRAODV) that tries to optimise routing overhead in the Route Discovery Process (RDP) of traditional reactive protocol AODV. Optimisation in TRAODV is achieved by detecting the waiting time required for Route Reply (RREP) procedure until receiving a *threshold* number of *efficient routes.*

Our second approach is also a link-disjoint multipath extension called "On-demand Route maintenance in Multipath AoDv" (ORMAD) which is an extension to TRAODV that improves the Route Maintenance Process (RMP) of traditional AODV protocol. Unlike TRAODV which immediately reinvokes a new RDP when detecting a link failure in the primary route, ORMAD first invokes a local repair procedure to fix the link failure before reinvoking a new RDP. ORMAD applies the mechanism of threshold waiting time and *efficient routes* to both phases RDP and RMP. Furthermore, it applies the local repair procedure only to *efficient routes.*

Our novel approaches in this thesis, TRAODV and ORMAD, are implemented and evaluated against two existing multipath extensions to AODV protocol and two traditional multipath protocols. The existing extensions to AODV used in the evaluation are a well-known protocol called Ad hoc On-demand Multipath Distance Vector (AOMDV) [17] and a recent extension called Multiple Route AODV (MRAODV) [13] which is extended in this thesis to the new approach TRAODV while the traditional multipath protocols used in the evaluation are Dynamic Source Routing (DSR) [15] and Temporally Ordered Routing Algorithm (TORA) [16]. Protocols are implemented using Network Simoulator-2 (NS2) and evaluated under the same simulation environment in terms of four performance metrics; packet delivery fraction, average end-to-end delay, routing packets overhead, and throughput.

In order to narrow down the research area, an experimental study is carried out in Chapter 3 for three traditional reactive ad hoc routing protocols, namely DSR, AODV, and TORA based on a simulation using NS2 to verify the feasibility of developing AODV protocol to new multipath extensions as it is well-known and well-proven ad hoc routing protocol, or there is any other candidate protocol. Hence, the overall performance of the traditional multipath protocols (DSR and TORA) is evaluated against the overall performance of the traditional single path protocol (AODV) and its extensions.

1.2 Motivation and Significance

MANETs gain an increasing significance in today's modern civilisation, especially with the enormous advancement of information technology and mobile communication. There are many applications where ad hoc networking is needed; for example, in military applications, rescue operations in natural disasters, sensor networks, and even initiating a conference using laptop computers in a Local Area Network (LAN). Such applications require a kind of instant networking regardless of any fixed infrastructure, and this is the idea behind MANETs which are very flexible networks and suitable for these types of applications.

The motivation of choosing the scope of multipath AODV for this research comes from the fact that the routing issue is considered one of the most challenging and interesting research areas in MANETs. Additionally, the results of the experimental study which is carried out in this thesis for the most common traditional routing protocols and some common extensions to AODV protocol shows that AODV is more desirable than the other compared protocols in MANETs, especially in the case of high mobility and high traffic load. The results also show that multipath protocols outperform single path protocols and the multipath extensions to AODV almost outperform the traditional multipath protocols in terms of the most common performance metrics.

As mentioned earlier in this chapter, multipath abstraction is considered as an advantage for routing issue so that multipath protocols are considered more reliable and robust. Furthermore, whenever detecting a link failure in a primary route, the source node can select the optimal route among multiple available routes. This mechanism enhances route availability and consequently minimises frequent re-establishing of RDP, saves energy, reduces frequent routing update, enhances data transmission rates, and increases the network bandwidth [18]. For these reasons, multipath routing is useful for many applications in MANETs such as heavy multimedia and real-time traffic, routing fault tolerance, diversity coding, link security strengthen and finally, load and energy balancing. Using multipath in these applications is covered in details later in Chapter 2.

1.3 Problem Statement

Single path abstraction requires a source node to re-establish a new RDP when detecting a link failure in the current primary route. Hence, it is considered as a significant drawback of traditional AODV routing protocol in MANETs. In ad hoc environment, so many multipath extensions to AODV are conducted focusing on the optimisation of multipath abstraction in both RDP and RMP of this protocol. In traditional AODV, a RDP is invoked on-demand whenever the current primary route fails due to a link failure. When a link failure is detected, a RMP starts by generating and sending a Route ERRor (RERR) packet to all nodes that have one or more routes involving the failed link to update their routing tables. Then, a new RDP is invoked to obtain an alternative route among multiple detected routes. AODV selects only a single route (the optimal) to be used for data transmission and the other routes are discarded. When a link failure is detected again, a new RDP is invoked again to obtain an alternative route, and so on. The main problem of the single path mechanism of AODV is that it increases frequent route rediscovery attempts and consequently increases delay and control overhead.

Many approaches are conducted to solve the main problem of the single path feature in AODV either the partial-route re-establishment or multipath establishment approaches [13]. For example, numerous early extensions to AODV propose a backup route to solve the problem of link failure in the primary route. However, the problem would not be solved if a link failure would be detected in the backup route itself. In order to overcome this problem, more recent extensions are developed to detect more than two routes for each destination in the network. Most of these extensions aim to detect as large number of multiple routes as possible regardless of the efficiency of those routes. These extensions usually have a lot of inefficient routes which lead to more routing overhead, especially in end-to-end delay, network bandwidth, and memory consuming. For example, numerous approaches of this type of extensions utilise RREP timeout (waiting time) used in traditional AODV which is not sufficient to detect all possible routes, and consequently many efficient routes can be missed due to the short period of the Route Reply (RREP) timeout. Some approaches extend the RREP timeout to detect all possible routes however, it is considered a long period so that many efficient routes that are detected early become inefficient due to the mobility of the nodes which leads to an increase of the probability of link failure occurrence in these routes. Thus, instead of waiting in the routing table for long time hopefully more routes may arrive, the efficient routes should be utilised by a source node as soon as possible to avoid the effect of the mobility on the links. In addition, only efficient routes should be stored in the routing table to minimise routing control overhead and, this is the first problem concerned by this research.

Most literatures of multipath extensions to AODV deal with the route maintenance problem by invoking a global route discovery to detect a new end-to-end route by sending a Route Request (RREQ) from the source to the destination via intermediate node(s). Invoking global route discovery frequently leads to an increased routing overhead and a greater consumption of the network resources such as bandwidth, energy, memory, and computing time. Instead, local route discovery can be invoked to minimise this overhead which is the second problem focused by this research.

The simulation results of the experimental study which is carried out in this thesis (Chapter 3) show that traditional multipath protocols outperform the single path protocol in terms of all performance metrics except average end-to-end delay. As shown by the results, the rate of routing packet overhead is less in a network that uses multipath routing. It also shows that using multipath routing protocols results in a higher throughput and packet delivery fraction than that in single path protocols. However, even with its single path feature, the overall performance of AODV is better than the individual performance of each traditional multipath protocol in terms of average end-to-end delay and it converges to large extent to their performances for the other performance metrics. Thus, AODV is proven as the more desirable protocol than the other protocols, especially in the case of high mobility and high traffic load, which means that it is feasible to develop many efficient extensions by combining AODV features with the multipath feature of some traditional protocols.

For these reasons, the two multipath extensions to AODV (AOMDV and MRAODV) are evaluated against the traditional multipath protocols in MANETs (DSR and TORA) in order to determine the starting point of our research. Simulation results show that both AOMDV and MRAODV have better average performance compared to the traditional multipath protocols in terms of all performance metrics except the routing packets overhead which is still better in traditional protocol TORA. In addition, even though that MRAODV enhances the routing packets overhead in AOMDV to a certain extent, a vital drawback in the average end-to-end delay appeared in MRAODV. Instead of enhancing the average end-to-end delay in AOMDV, the performance of MRAODV is reduced compared to AOMDV performance in terms of average end-to-end delay.

The results of the experimental study prove that MANETs still need developing more efficient extensions to AODV to overcome the drawbacks of the existing extensions such as AOMDV and MRAODV. Thus, the novel approaches TRAODV and ORMAD are developed to optimise routing packet overhead and average end-to-end delay of multipath extensions to AODV.

1.4 Research Contributions

This thesis presents two new approaches called TRAODV and ORMAD as efficient extensions to AODV that are developed to overcome the drawbacks of the existing extensions such as AOMDV and MRAODV. Developing these two novel approaches aims to optimise routing packet overhead and average end-to-end delay which are the vital disadvantages in the performance of the existing multipath extensions to AODV.

TRAODV approach is a link-disjoint multipath establishment approach focuses on optimising RDP of AODV routing protocol in MANETs (see Chapter 4). TRAODV aims to reduce routing overhead by detecting the waiting time needed to receive *threshold* number of efficient routes. Furthermore, it tries to decrease routing delay overhead and increase route availability in the routing table by calibrating the RREP timeout so that most efficient routes can be detected without causing a link failure occurrence in the efficient routes that are detected early. The link-disjoint feature of TRAODV helps the protocol to detect independent efficient routes which decrease the probability of sharing link failures between different available routes and this consequently reduces routing overhead.

ORMAD approach is a link-disjoint multipath extension to TRAODV (see Chapter 5) that focuses on optimising RMP of AODV routing protocol in MANETs by applying a RMP only to efficient routes starting with the most optimum route and ending with the least optimum route. Also, ORMAD still utilises the mechanism of TRAODV in its route discovery process.

Another novel aspect of this thesis is that it introduces an analytical model for ORMAD approach so that it describes the whole process of a multipath extension to AODV, especially its two main core processes, RDP and RMP. The analytical model of ORMAD also describes how these two core processes interact with each other in multipath routing with regard to two performance metrics, namely total number of detected routes and route efficiency. In addition, the analytical model introduced in this thesis for ORMAD can be applied not only to multipath extensions to AODV but also to any other on-demand multipath protocol in MANETs with some modifications that may be needed according to the nature of each protocol. The analytical model of ORAMD is implemented and tested using Matlab 6.0 to prove the behaviour of the total number of multiple routes and the route efficiency in terms of different scenarios of connectivity, mobility, and route reply waiting time.

1.5 Research Scope

Figure 1.1 shows the scope of this research inside MANETs area. The two approaches developed in this research are shown in the bottom of the diagram. These approaches represent the two goals of this research which are improving RDP and improving RMP respectively in multipath AODV.

1.6 Research Methodology

The following steps summarise the methodology used to achieve the goals of this research:

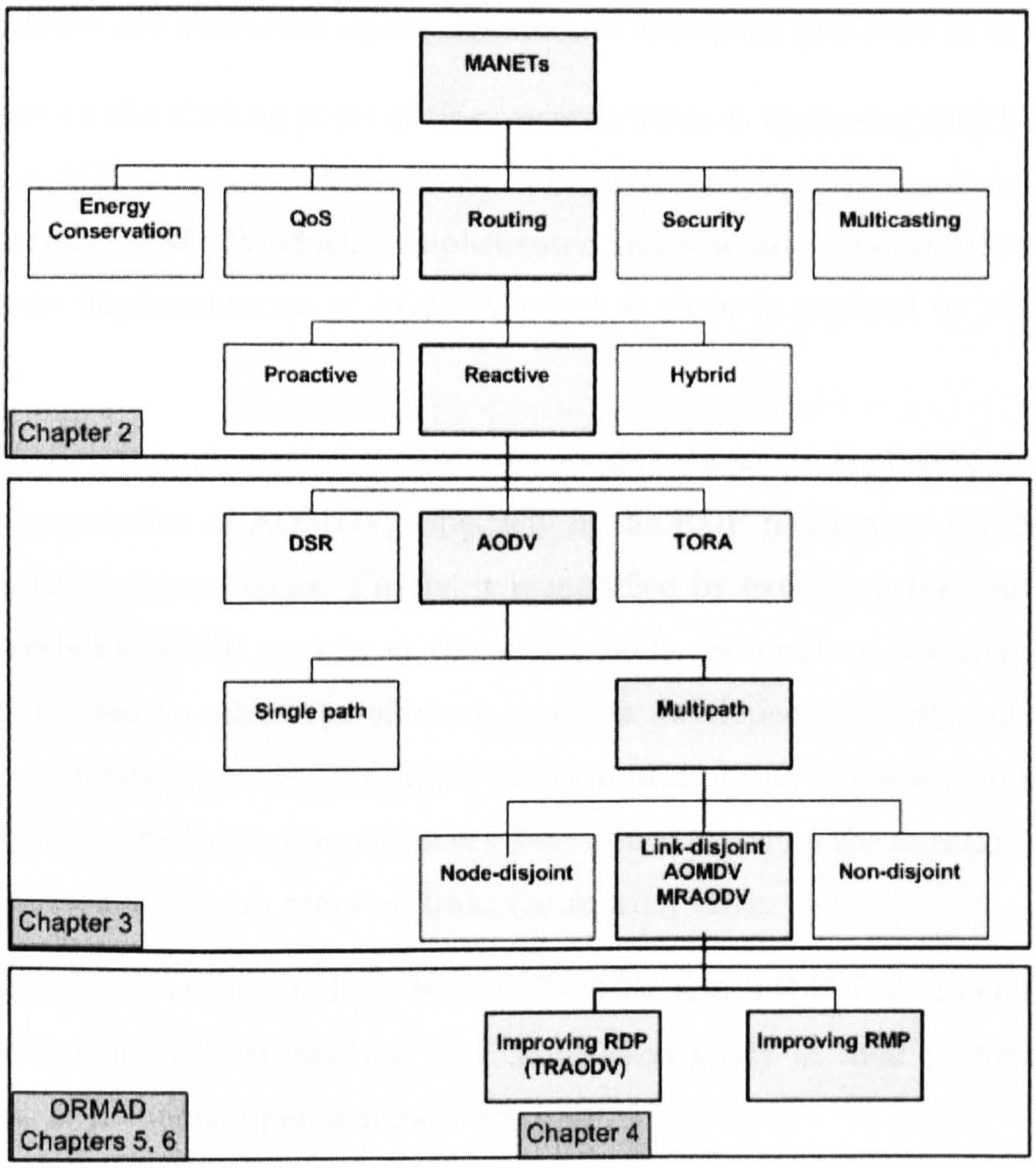

Figure 1.1: Scope of the research

- Initially, an extensive study in MANETs is employed, especially in the area of routing protocols and multipath routing is carried out.

- The primary goal of the extensive study is to identify and establish the concrete boundary of multipath routing related work and consequently determine the scope and the starting point of this research.

- An experimental evaluation is carried out based on NS2 simulation to narrow down the research area and to recognise the lack in the existing protocols. This is achieved by analysing through a simulation three traditional routing protocols in MANETs including AODV. In addition, two multipath extensions to AODV are evaluated against traditional multipath protocols in MANETs.

- Based on the starting point of this research which is improving multipath routing in AODV, MRAODV is chosen to be optimised, and the result is our novel approach TRAODV which is implemented and evaluated against MRAODV using the implementation of AOMDV which is recently involved by NS2 version 2.26.

- TRAODV is implemented so that some modifications are applied to the original implementation of AOMDV, especially in the RDP mechanism which is modified using several steps. Firstly, it is modified by extending the waiting time of receiving RREP packets at the source node. Secondly a selection criterion that is used to select the efficient routes is developed. Thirdly, all detected routes (multiple routes) are stored in the routing table of the source node. Finally, all inefficient routes which are determined based on the selection criterion mentioned above are removed from the routing table.

- A simulation is executed for both MRAODV and TRAODV under the same environment with an analysis and comparison study of their performance in terms of predefined performance metrics.

- Determining the second point of this research which is improving the route maintenance process, RMP, of multipath AODV using the concept of local repairing. A simulation is executed for both ORMAD under the same environment of TRAODV simulations. Simulation results of ORMAD performance are evaluated against TRAODV and the other extensions to AODV in terms of predefined performance metrics.

- The third point is introducing an analytical model for the whole multipath routing process of ORMAD. The analytical model is implemented and tested numerically using Matlab to prove the behaviour of the total number of multiple routes and the route efficiency in terms of different scenarios of connectivity, mobility and route reply waiting time ratios.

1.7 Thesis Organisation

This thesis is organised into nine chapters including this chapter. The following paragraphs provide brief descriptions of the remaining chapters of this thesis.

Chapter 2 is concerned with firstly overview, characteristics, factors, applications, issues, and a reference model of MANETs. Secondly, it presents a brief overview of the most significant issues in MANETs such as routing, QoS, security, and multicasting. Thirdly, routing issue in MANETs is more focused including characteristics, routing issues, requirements, and classification of routing protocols in MANETs. Finally, a literature review for multipath routing in MANETs is presented including its applications, classification, and design issues.

Chapter 3 presents firstly an experimental study by means of NS2 simulation which focuses on comparing the performance of three traditional reactive routing protocols in MANETs. Simulation environment, input parameters, and performance metrics, and results of the simulation are presented. Secondly, a simulation-based evaluation using NS2 is presented to evaluate two multipath extensions to AODV against two traditional multipath protocols in MANETs using the same simulation environment, input parameters, and performance metrics of the first study. The evaluation of all protocols with a general discussion is presented in the end of the chapter.

Chapter 4 presents TRAODV approach. Simulation environment, input parameters, and performance metrics of TRAODV simulation are presented in this chapter while the results of the study and evaluation of TRAODV are presented later in Chapter 7.

Chapter 5 presents ORMAD approach introducing an analytical model for the whole process of multipath AODV routing, especially for the two main core processes, RDP and RMP. The implementation of ORMAD using Matlab is presented in the end of this chapter. Applying testing data, input parameters, and defining performance metrics of ORMAD implementation are presented in this chapter while the results of the study and evaluation of ORMAD are presented later in Chapter 7.

Chapter 7 presents the results of the research including TRAODV and ORMAD simulation results. The results of the numerical implementation and testing of formalising the relevant concepts of ORMAD approach are presented in the end of the chapter.

Chapter 8 presents the conclusions and the future work of the research.

Chapter 2

Mobile Ad Hoc Networks (MANETs)

2.1 Introduction

MANETs are considered a vital part in beyond third generation wireless networks [4][5]. A MANET is a new wireless networking paradigm developed for autonomous mobile nodes. MANETs do not use any kind of fixed infrastructure which is usually a significant part of traditional wireless local area networks such as WLANs, and thus MANETs work in a cooperative and distributed environment [2][6].

Since it is infrastructureless which means that no Access Points (APs), no routers, no configuration prior to setup of the network, and no predetermined topology [14], a MANET is also considered a self-creating network. For these reasons, a MANET is considered also a self-organising and self-administering network because no central control can be applied in creating the network. Actually, it is difficult to apply any kind of central administration on MANETs such as central routing, authentication, or congestion control due to the dynamic nature of the network topology in MANETs.

For all reasons mentioned above, MANETs are suitable for many significant applications such as military, emergency, collaboration, and ubiquitous computing.

This chapter presents an overview of MANETs covering the characteristics, applications, challenges, and a reference model of MANETs. The most significant issues in MANETs are reviewed which include routing, QoS, security, and multicasting. Since routing in MANETs is the general scope of this research, routing is more focused later in Section 2.8 and a review of state-of-the-art multipath routing is presented in Section 2.9.

2.2 MANETs Overview

MANETs are often related to the concept of WLANs which are well-known as single hop and infrastructure-based wireless networks [2][5]. This means that there is at least one fixed Access Point (AP) that governs the transmission between different mobile nodes inside a WLAN. An AP functions as a bridge between the stations and an existing network backbone [7]. Also, WLAN is often connected to a wired network via a hub or switch. Existence of an AP can strongly help controlling the security and QoS issues in a network. In WLAN, no routing is needed between different mobile nodes inside the network because the communication is done via the AP in a single hop manner. WLAN implementations often include wireless network standards developed by Institute of Electrical and Electronics Engineers (IEEE) 802 project (IEEE 802.11, IEEE 802.11b, IEEE 802.11g, IEEE 802.11a, and IEEE 802.11n [20]) and High Performance Radio Local Area Network Type 2 (HiperLAN2), the European version of IEEE 802.11a which is being developed by European Telecommunications Standardisation Institute (ETSI) Broadband Radio Access Networks (BRAN) project [19]. Most of these standards operate at a frequency of 2.4GHz except IEEE 802.11a which operates at 5GHz. The bandwidths (transmission rates) of these standards are 2Mbps for IEEE 802.11, 11Mbps for IEEE 802.11b, 54Mbps for IEEE 802.11g and IEEE 802.11a, and 100Mbps for IEEE 802.11n [20]. Figure 2.1 illustrates a single hop WLAN with one AP.

A MANET is a new wireless networking paradigm for mobile hosts. As mentioned earlier in this chapter, MANETs do not depend on any kind of fixed infrastructure. Instead, hosts (nodes) depend on each other in a cooperative manner to keep the network connected. Thus, the goal of mobile ad hoc networking is to provide an ubiquitous communication and computing which can be deployed rapidly independent of a pre-existing infrastructure such as APs or base stations [21]. Hence, a MANET can be defined as a peer-to-peer network that enables wireless clients to communicate amongst each other without depending on any infrastructure. It can be also defined

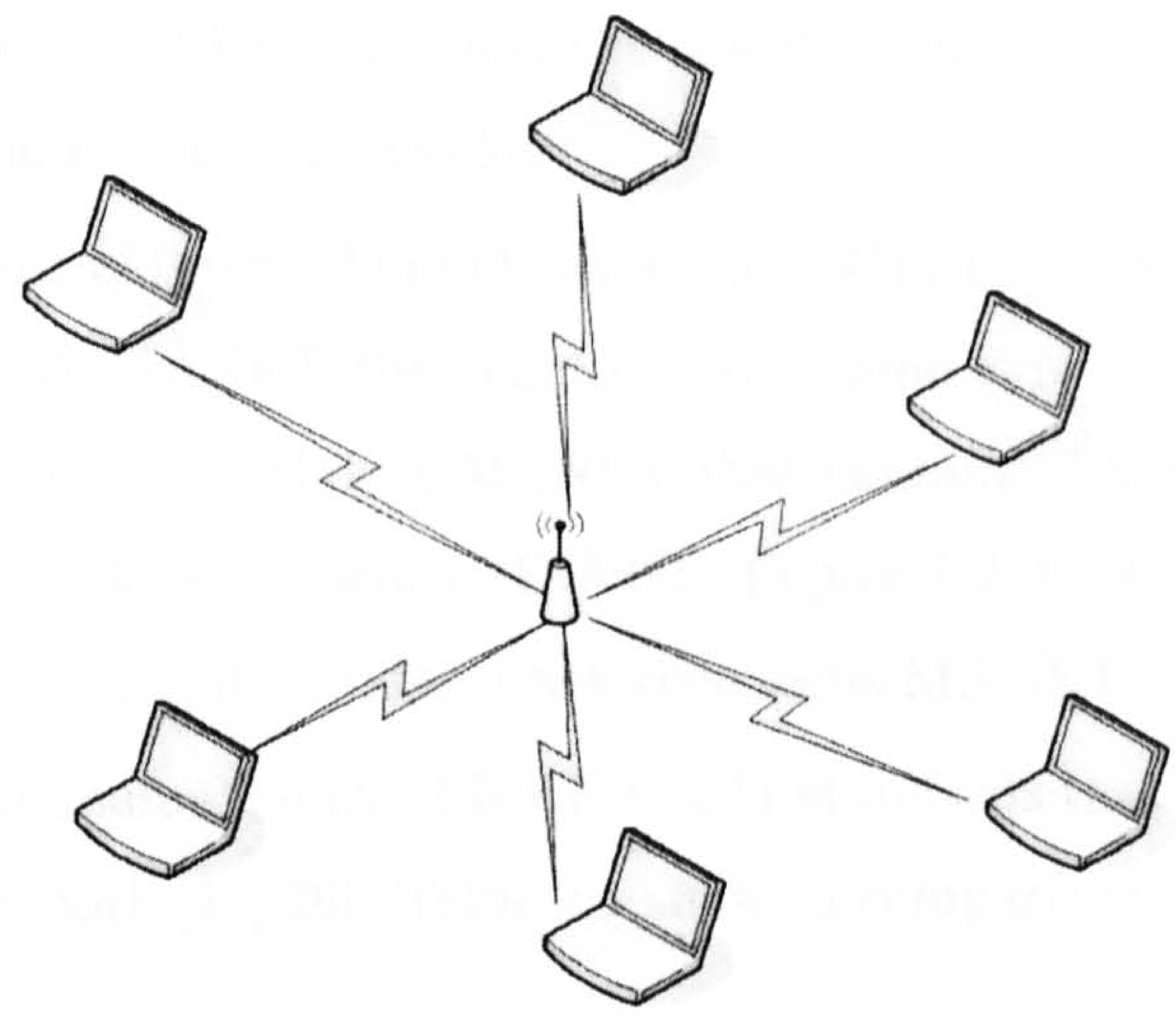

Figure 2.1: An example of a single hop WLAN with one AP

as a collection of mobile nodes that form a dynamic topology and highly resource constrained network [1][2]. Unlike WLAN which is a single hop network, MANET is a multi-hop network which means that nodes in a network cooperate to perform the major functions of the network [3].

MANETs encounter more challenges in routing, QoS, energy conservation and security [7] due to the absence of infrastructure, its cooperative nature, high mobility, resource constrains (power, storage, and bandwidth) [22] and finally, the dynamic topology of nodes operating in MANETs environment.

Ad hoc networking is not a new concept because it was initiated in Defence Advanced Research Projects Agency (DARPA) Packet Radio projects [23] for military applications since 1970s as a technology for dynamic wireless networks. Developing MANETs was interested commercially in the last two decades and it has recently grown due to the development in wireless communications.

A new working group is formed for MANET within the Internet Engineering Task Force (IETF) [4] to develop standard Internet routing support for mobile IP autonomous segments and also to develop a framework for IP-based protocols in MANETs. The increasing improvement in the recent IEEE standards of 802 project for wireless networks [24] has increased the research interest in the field of wireless Internet and mobile IP-based networks.

Based on the type of involved mobile nodes, a MANET can be either homogeneous or heterogeneous. A MANET that contains the same type of all mobile nodes is considered a homogeneous, while a MANET that contains different types of mobile nodes is considered a heterogeneous MANET. Figure 2.2 illustrates a homogeneous MANET while Figure 2.3 illustrates a heterogeneous MANET.

MANETs use the same family of IEEE 802.11 standards that are used in WLANs in addition to Bluetooth [25][26]. Table 2.1 shows a comparison between WLAN and MANET.

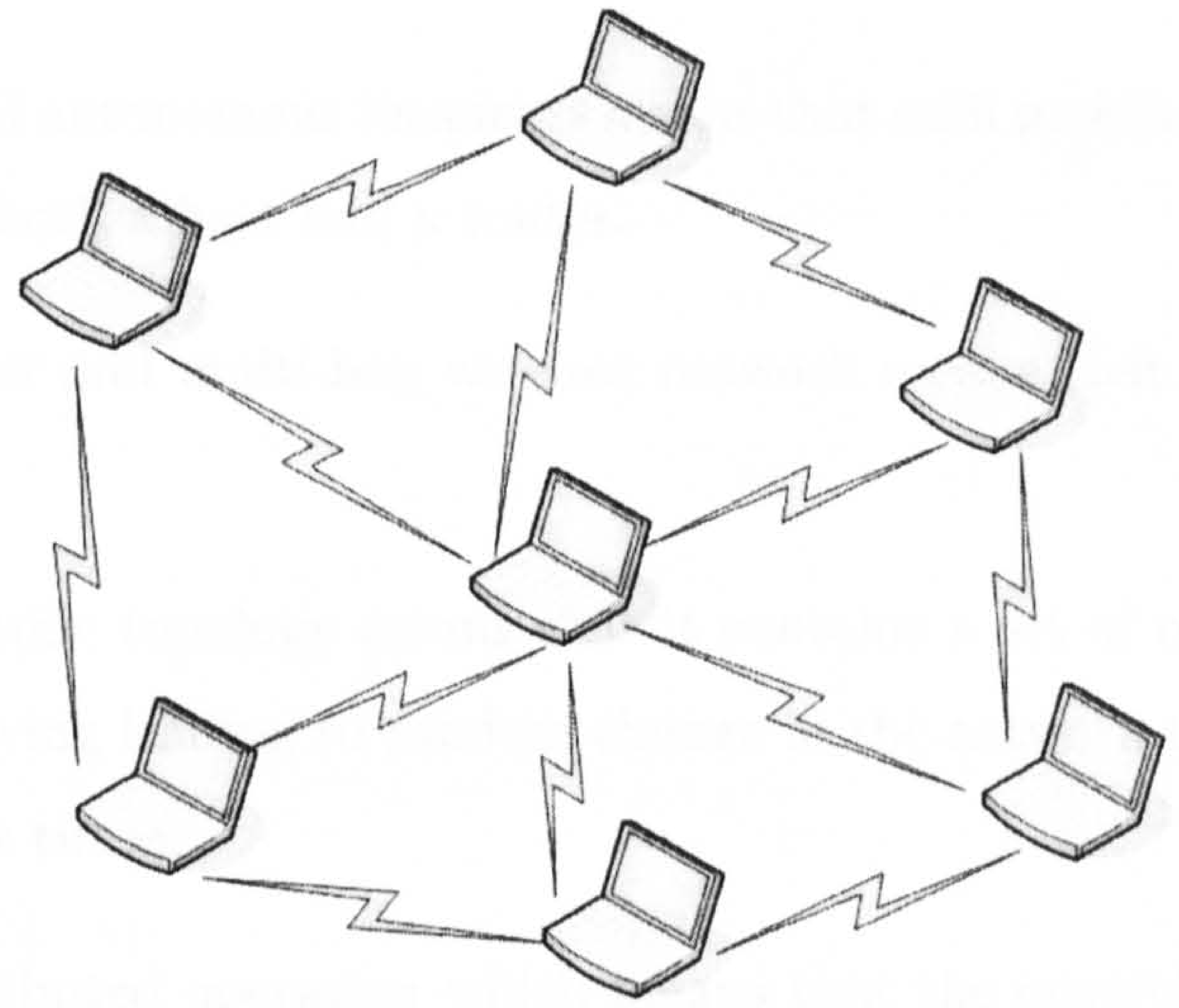

Figure 2.2: An example of a homogeneous MANET

2.3 Characteristics of MANETs

Request For Comments (RFC) 2501 document [27] which is published by MANET working group within the IETF describes the main characteristics of MANETs which differs from the characteristics of traditional wireless local area networks such as WLANs due to the dynamic and the infrastructureless natures of MANETs [28]. The most significant characteristics of a MANET are summarised as follows:

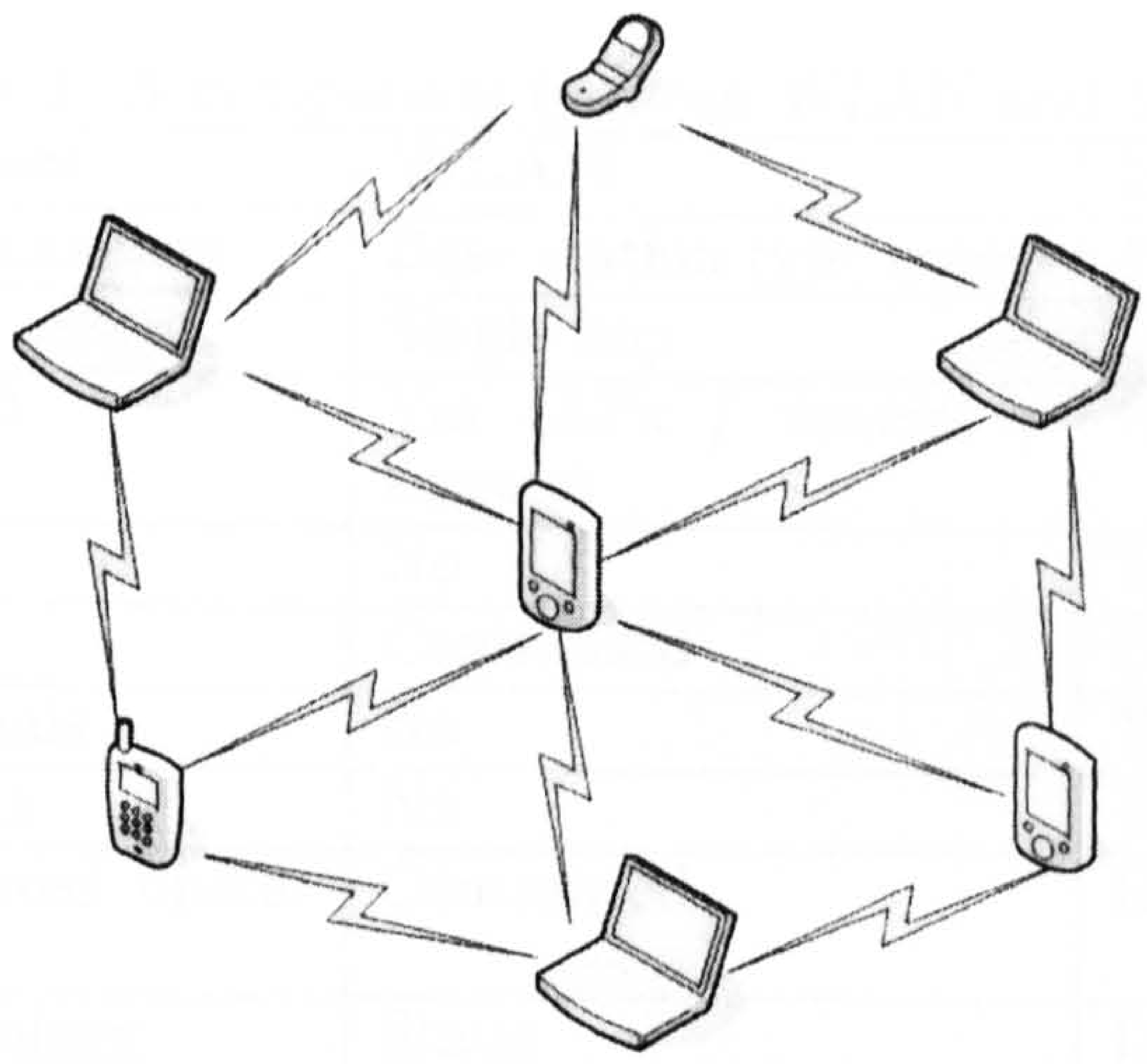

Figure 2.3: An example of a heterogeneous MANET

- A collection of autonomous terminals means that each mobile node in a MANET functions as both a host and a router.

- A peer-to-peer and multi-hop wireless network means that no central routing in MANET.

- It has a dynamic topology means that it contains a set of nodes that are continuously moving leading to random change in the network topology rapidly at unpredictable times.

- It has a distributed operation which means that the control and management of the network is distributed among the nodes due to the absence of any type of infrastructure that usually supports the central control of the network operations. The nodes involved in a MANET should collaborate amongst each other, and each node acts as a host and router at the same time to implement network functions such as security and routing.

- It can be rapidly deployed.

- It does not rely on pre-existing infrastructure.

- A bandwidth-constrained network with variable capacity links.

Table 2.1: A comparison between WLAN and MANET

Comparison Aspect	WLAN	MANET
Communication mechanism	Base station type access	Peer-to-Peer
Single/multi-hop	Single hop	Multi-hop
Infrastructure-based	Yes (APs / routers / servers)	No
Self-configurartion	No	Yes
Security policy	Centralised	Distributed
Autonomous terminals	No	Yes
Mobile hosts/routers	No	Yes
Centralised/distributed operation	Centralised	Distributed
Static/dynamic topology	Static	Dynamic
Bandwidth-constrained network	No	Yes
Routing	Easy (rarely needed)	A big challenge
Power awareness	Does not matter	Yes
QoS guarantee	Can be guaranteed easily	A big challenge
Scalability	Easy	A big challenge
Multicasting	Easy	A big challenge
Typical applications	Home/enterprise networking	Military/emergency

- Self-adapts to the connectivity and propagation patterns.
- Adapts to traffic and mobility patterns.
- It has a limited physical security, especially in the absence of any centralised authentication or encryption. Existing link security techniques are often applied within wired networks and WLANs to reduce security threats however, MANETs are generally more prone to physical security threats than are wired networks or WLANS.
- It has an energy-constrained operation so that energy conservation of batteries in mobile nodes may be considered one of the most significant design criteria for optimisation in MANETs.

There are several reasons (advantages) why MANETs are considered good candidates for mobile networking, the most significant reasons for that are the easy to use and speedy deployment, robustness and low cost because there is no dependence on any type of infrastructure, and the basis of ubiquitous computing such as wireless Internet.

The most significant disadvantages of MANETs are the complexity of routing because of the consistently moving nodes, mobility and dynamic topology, vulnerability of security due to the cooperation principle in MANETs, and the low computing power due to small devices used in MANETs.

2.4 Applications of MANETs

MANETs are very flexible networks and suitable for several types of applications, as they allow the establishment of temporary communication without any pre-installed infrastructure. The following is a summary of the major applications in MANETs:

- Personal communications (e.g. cell phones, laptops and ear phone).
- Cooperative environments (e.g. taxi cab network, meeting rooms, sports stadiums, boats and aircrafts).
- Emergency operations (e.g. policing, fire fighting and earthquake rescue).
- Military environments (battlefield).
- Conferencing (using mobile nodes).
- Enterprise network.
- Vehicle network.
- Home network (almost used for PANs [28]).
- Hospitals (e.g. healthcare).
- Wireless mesh networks (very reliable networks that are closely related to MANETs, the nodes of a mesh network generally are not mobile [29]).

- Wireless sensor networks (a very hot research area of ad hoc networking which includes fixed networks or mobile sensors [2][6]).

- Hybrid wireless networks (which aims to cost savings, performance improvements and enhanced resilience to failures [30]).

- Collaborative and distributed computing.

2.5 Challenges and Issues of MANETs

There are several challenges and factors specifically important for ad hoc networking design and implementation. The most significant challenges and factors affecting MANETs are summarised as follows:

- Application/Market penetration: multi-hop technology is not commercialisable till now [31] which can be justified by the limitations of the short coverage area of the wireless products that belong to the standard of IEEE 802.11.

- Design/Implementation: because MANETs have limited physical security, bandwidth-constrained operation, and they are energy-constrained, the design and implementation of MANETs must be reliable, manageable, survivable, and secure.

- Limited wireless transmission range: depends on the capabilities of wireless technology.

- Operational/Business-related: how to manage the network and how to bill for services.

- Mobility: often considered the first enemy of the designer of MANET [2].

- Scalability: a MANET can grow to thousands of nodes in some applications such as large environmental sensor fabrics, battlefield deployments, and urban vehicle grids. Unlike infrastructure-based networks, It is difficult to handle the scalability in a MANET due to unlimited and random mobility, and the infrastructureless nature of MANETs [21].

- Energy conservation: most ad hoc nodes such as Laptops, Personal Digital Assistants (PDAs), and sensors are often power supplied using batteries which have limited power. Thus, energy conservation is a big challenge for MANETs.
- Address assignment.
- Power budget versus latency.
- Cross-layer interaction.
- Incompatible standards.

The major issues that affect the design, deployment, and performance of an ad hoc wireless system are summarised bellow. The four most important issues in MANETs are listed first in the following list and they are covered in more details later in this section.

- Routing
- QoS provisioning
- Security
- Multicasting
- Energy management
- Medium access scheme
- Pricing scheme
- Transport layer protocols
- Self organisation
- Addressing and service discovery
- Scalability
- Deployment considerations

2.5.1 Routing

Routing support between any pair of nodes has become one of the most significant issues in MANETs because the topology of the network is constantly changing. Most ad hoc routing protocols are based on reactive (on-demand) routing instead of proactive (table-driven) [3]. Proactive protocols update periodically routing information to various nodes in the network so that a source node can find the route to a destination whenever needed. Unlike proactive protocols, reactive protocols should discover and select the optimal route on-demand among multiple routes that are detected during the route discovery process. A hybrid protocol is a combination between both proactive and reactive protocols [2][3].

Routing in MANETs differs from routing in traditional wired and wireless networks [28][32] due to the following reasons:

- Both router and host (the node itself is the router and the host at the same time) are mobile. Thus, both route discovery process and route maintenance process of a routing protocol are affected by the mobility of the node. Link failure/repair may be increased when nodes move fast, which does not matter in traditional networks.

- The infrastructureless nature of a MANET causes a difficulty to use any centralised administration of routing which is often needed for the deployment process of a routing protocol in traditional networks. The operation in MANETs is fully distributed including the coordination regarding routing information exchange. Another issue related to this cooperation is the security issue which is usually preferred to be centralised and under control of the administrators in traditional networks.

- The scarce energy and link capacity of a node in MANETs [22] lead to adopt new performance criteria to measure the routing efficiency. A most significant example of such new criterion which is associated with MANET concept is route stability despite mobility and energy consumption. In addition to the old criteria of traditional networks such as bandwidth consumption, routing packet overhead, routing delay overhead, security awareness, and QoS awareness, this new criterion should be taken into account when designing an ad hoc routing protocol.

2.5.2 QoS Provisioning

The notion of QoS is a guarantee of a set of predetermined service performance constraints to be satisfied by the network to the user [33]. In other words, QoS is the performance level of services offered by a service provider or a network to the user in terms of many performance metrics of QoS such as the average end-to-end delay, packet delivery, and available bandwidth. QoS provisioning often requires negotiation between the host and the network regarding the resource reservation schemes, priority scheduling, and call admission control. Hence, providing different quality of service levels in a highly changing environment is a significant issue in MANETs. In MANETs, the presence of additional bandwidth, link and medium constraints, and high change in network topology makes QoS provisioning more difficult than in fixed wired networks, which only need to deal with static constraints such as bandwidth, memory, or processing power [7]. To support multimedia services in MANETs, an adaptive QoS must be implemented over the traditional resource reservation techniques [2][8].

2.5.3 Security

Ad hoc networks are highly vulnerable to security attacks and dealing with this issue is one of the main challenges of MANET developers. In addition to the common vulnerabilities of wireless connections, a MANET has its own particular security problems due to various reasons such as malicious attacks of a neighbour node, shared broadcast radio channel, insecure operating environment, lack of central authority, lack of association among nodes, limited availability of resources, and physical vulnerability. The most interested attributes of security in MANETs are availability, confidentiality, integrity, authentication, and non-repudiation [8][10][34].

In brief description, availability ensures the survivability of network services despite denial of service attacks. Confidentiality ensures that certain information is never disclosed to unauthorised entities. Integrity guarantees that a message being transferred is never corrupted. Authentication enables a node to ensure the identity of the peer node which is communicating with. And finally, non-repudiation ensures that the origin of a message cannot deny the message sending [34][35]. The major security threats/attacks that exist in MANETs are summarised as follows:

- Denial of service
- Passive eavesdropping
- Signaling attacks
- Resource of service (e.g. energy depletion, buffer overflow)
- Host impersonation.
- Information disclosure.

2.5.4 Multicasting

Multicast routing is another significant issue of MANETs because the multicast tree is not static in MANETs due to the random movement of nodes in the network. Routes of each pair of nodes may potentially contain multiple hops. This type of communication is more complex than the single hop communication. Multicast routing becomes necessary when multicast packets should be sent to groups in several networks. In MANETs, multicasting plays a vital role in several applications such as emergency, rescue operations, and military operations. Node mobility with the power and bandwidth constraints make multicast routing very challenging in MANETs [2][36].

2.6 MANET Layers

Network architecture can be described generally using a reference model that describes the layers of hardware and software necessary to transmit data between two points or to enable interoperating of multiple devices/applications in a network. Reference models are necessary to increase compatibility in the network between different components from different manufacturers [37]. The Open Systems Interconnection (OSI) reference model proposed by the International Organisation for Standardisation (ISO) consists of seven layers [38] which are ordered from layer 1 (the lowest) to layer 7 (the highest) as shown in Figure 2.4. These seven layers are (from lower to higher) the physical layer, data link layer, network layer, transport layer, session layer, presentation layer, and the application layer.

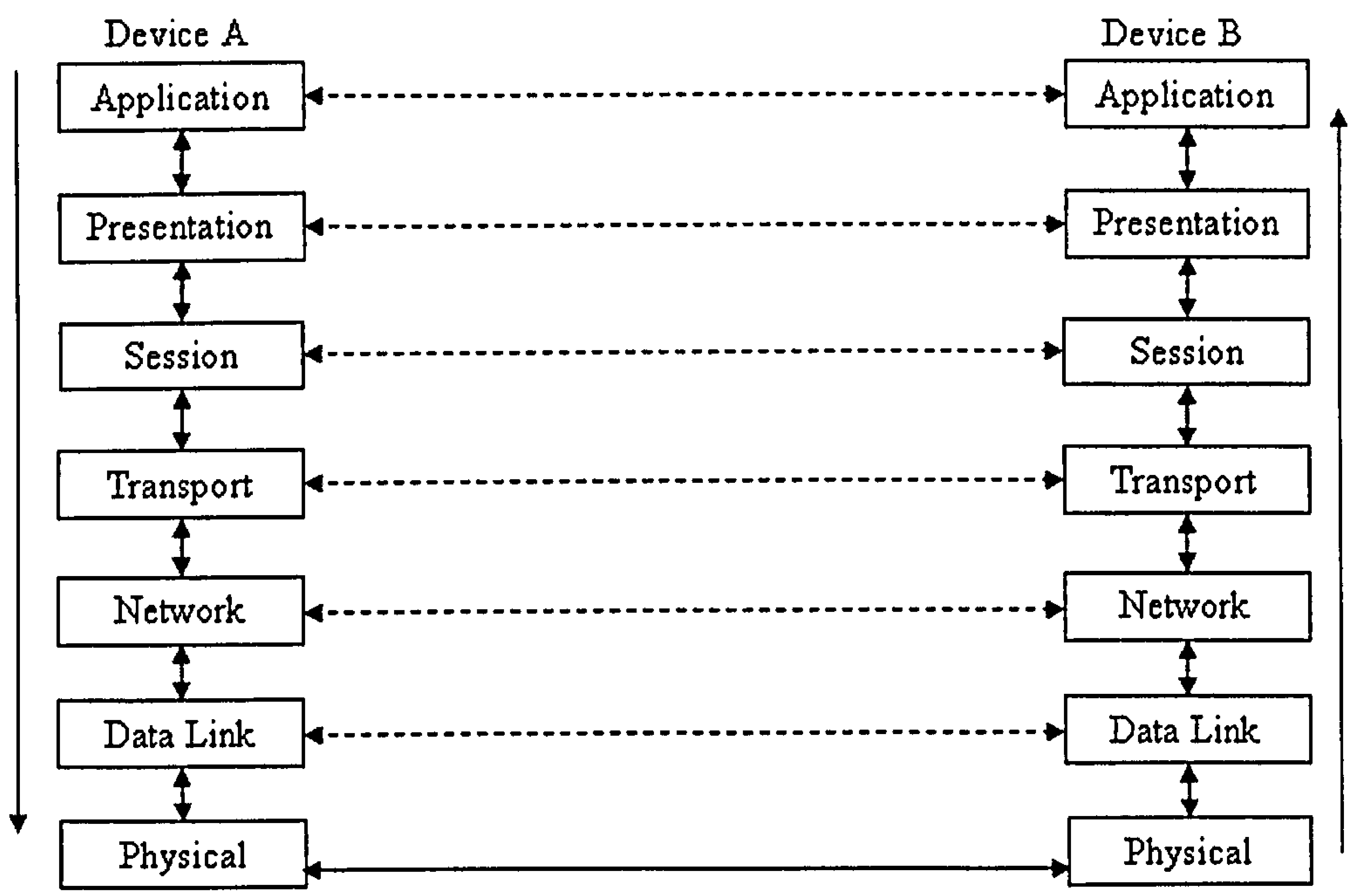

Figure 2.4: ISO-OSI reference model

Physical layer handles the transmission of bits over a communications channel. It is responsible for bit encoding and determining the voltage levels to be used for transmitting the bit stream over the physical medium and the time duration of each bit. It also concerns other physical specifications such as connectors, media choice, and modulation techniques. The functions of data link layer are to coordinate the access of multiple nodes to a shared medium, take the data and transforming it into a frame with header, control and address information, error detection code, flow control, and Medium Access Control (MAC) addressing. Network layer is responsible for creating, maintaining and ending network connections. It transfers a data packet from node to node within the network. In other words, it is responsible for routing (scope of this thesis), congestion control, IP addressing, and internetworking. Transport layer provides an end-to-end error-free network connection, and makes sure the data arrives at the destination exactly as it left the source. Session layer is responsible for establishing sessions between users while presentation layer performs a series of functions necessary for presenting the data package properly to the sender or receiver such as encryption and compression.

The highest layer is the application layer which enables the user to access the network. The main role of this layer is to handle frequent disconnection and reconnection with peer applications and to supports data transmission and services between users such as electronic mail and remote file transfer.

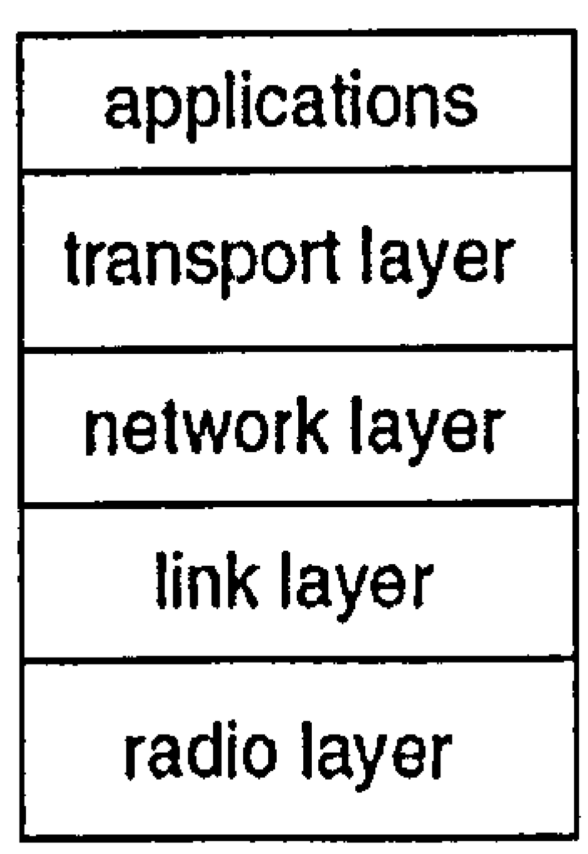

Figure 2.5: A MANET architecture of 5-layer reference model

A MANET architecture is suggested in most literatures of MANETs using a 5-layer reference model [7][39] as shown in Figure 2.5. The five layers suggested for MANETs are radio layer (instead of physical layer), link layer, network layer, transport layer, and applications layer. Figure 2.6 shows a 5-layer model proposed by [7] for MANETs with the corresponding research issues associated with each layer. As shown in the Figure, the three higher layers in ISO-OSI reference model (L5, L6 and L7) are merged in one layer (L5) in MANET's reference model. The lower layers (L1, L2, L3 and L4) are identical in the two reference models and their functions are also identical with more challenges encountered due to the nature of MANETs.

Layer	**Challenges in the layer**	**Cross-layer challenges (All layers)**
L5: Application layer Presentation layer Session layer	New/killer applications Network auto-configuration Location services Security (authentication and encryption)	Energy conservation QoS Reliability Scalability Network simulation Performance optimization H/W and S/W tools support
L4: Transport layer	TCP adaptation Back off window	
L3: Network layer	Routing IP addressing Optimization Multicasting	
L2: Data link layer	Media access control Error control Optimization	
L1: Physical layer	Spectrum usage/allocation	

Figure 2.6: MANET layers and the corresponding research issues

2.7 Topology Structures in MANETs

There are two types of topology structures/architectures in MANETs, Flat and Hierarchical structure. In a flat structure, all nodes in a network are at the same level and have the same routing functionality. Flat routing is simple and efficient for small networks. The problem is that when a network becomes large, the volume of routing information becomes larger leading to spend long time for routing information to arrive at remote nodes [3][8][40]. For large networks, hierarchical (cluster-based) routing may be used to solve the above problem. Characteristics of a flat structure in MANETs are summarised as follows:

- Nodes are at the same level which means that they have the same functions and responsibilities.
- There is no hierarchy/clustering in the network which means that the whole network is one cluster.
- All nodes cooperate for routing and security policies which means that it is fully distributed network.

In hierarchical routing, nodes in a network are dynamically organised into partitions called clusters, and then clusters are collected again into larger partitions called super-clusters and so on. Organising a network into clusters maintains a relatively stable network topology. Clusters limit the high dynamics of membership and network topology. However, less volume of routing information is propagated across a long distance in the network. This information contains only stable and high level information such as the cluster level or the super-cluster level. Hence, the routing overhead may be largely reduced using hierarchical routing [3][8][40][41]. Characteristics of a hierarchical structure in MANETs are summarised as follows:

- Consists of more than one level.
- Nodes are collected in clusters.
- Each cluster has a cluster head.
- Routing is accomplished through cluster heads.
- Heads keep locations information for clusters.

- There is a sort of centralisation that leads to lower reliability, easier routing, and better security.
- Cluster heads may consume more power and bandwidth than other members.

2.8 Routing in MANETs

Since routing in MANETs is the main scope of this thesis, it is focused again in more details in this section which presents a review for routing in MANETs covering characteristics, issues, requirements, and classification of routing protocols.

2.8.1 Overview of routing issues in MANETs

Routing is the most challenging and interesting research area in MANETs. It can be defined as detecting and maintaining the optimal route to send data packets between a source and destination via intermediate node(s) in a network [2][41].

In addition to its basic function, ad hoc routing issue has a coherent relationship with the most significant basic operations of the network such as QoS, security, bandwidth, and power constraints [1][42]. Thus, so many routing approaches in MANETs concern such relationship and so many titles of these approaches concern a sort of combination between routing issue and other issues such as QoS, power, and security. The responsibilities of a routing protocol in MANETs are almost concentrated in the two core processes of any routing protocol, RDP and RMP. Thus, it is useful to summarise the responsibilities of a routing protocol with regard to these two processes as follows:

- Exchanging route information.
- Detecting one or more feasible route(s) to a destination and selecting the optimal route based on criteria such as hop count and/or delay time.
- Handling the lifetime of the route.

- Handling the lifetime of wireless links.
- Gathering information about the route breaks (due to the involved link failures).
- Repairing the broken routes.
- All the above functions should be performed with minimum processing power and bandwidth.

In traditional routing protocols, each node in the network maintains a routing table which lists the next node for each destination that can communicate the source node. The routing table is usually designed using a distributed data structure. The goal of a routing protocol is to ensure that the overall data structure of all routing tables in a network contains a consistent and correct view of the actual network topology. Some troubles can be encountered due to the inconsistency and incorrect information of routing tables:

- Packets can loop in the network.
- Packets can be dropped.
- Routing delay overhead can increase.
- More energy of the nodes can be consumed.

Since routing in MANETs is very hard due to its dynamic topology, a variety of new routing protocols in MANETs have been developed in recent years taking into account the nature of MANETs. The design problem of a routing protocol in MANETs is not simple since an ad hoc environment introduces new challenges that are not present in traditional networks. A routing protocol of MANET should be capable to handle a very large number of hosts with limited resources such as bandwidth and energy.

The main challenge of a routing protocol in MANETs is that it must deal with the host mobility which means that the hosts can frequently move to various locations in short time duration. Hence, all hosts of a MANET act as routers and must participate in the RDP and RMP of the routes to the other hosts. For ad hoc routing protocols, it is essential to reduce routing messages overhead despite the increasing number of hosts and their mobility. Keeping the routing table small is another important challenge, because the increasing of the routing table will affect the control packets sent in the network which leads to increase routing control overhead [2][8][43].

All ad hoc routing protocols consist of the following two main phases (also called processes or components):

- Route discovery process, RDP, which is the process of finding a route between two nodes.
- Route maintenance process, RMP, by which a source node detects if the network topology has changed leading to break the current primary route due to node moving out of the range of the sender, then the failed route is repaired or an alternative route is detected by invoking a new RDP. RMP is considered a big challenge, especially in reactive ad hoc routing protocols.

2.8.2 Characteristics and design issues of an ad hoc routing protocol

Many characteristics and issues must be taken into account when designing an ideal routing scheme for MANETs. MANET working group defines some desirable qualitative properties for ad hoc routing protocols [44]:

- **Distributed operation:** this property is essential to MANETs to enable any host in the network join or leave the network whenever it decides.
- **Loop-freedom:** this property refers to avoiding packets spinning around in the network for arbitrary time.
- **Demand based operation:** ad hoc routing does not have to update the status of the links. Instead, it can discover the valid route(s) as needed (on-demand).

This mechanism may increase route discovery delay overhead however, bandwidth and energy resources can be more efficiently utilised if this mechanism is implemented intelligently.

- **Security**: because of the vulnerabilities in the physical security, ad hoc routing protocols are exposed to many types of attacks. Securing routing protocols must be taken into account in modern communication, especially for mobile nodes that are vulnerable to intrusion due to broadcasting.

- **Sleep period operation**: this property has to reduce the energy used by hosts and a routing protocol in MANETs should be able to deal with sleep periods effectively.

- **Unidirectional link support**: many routing protocols in MANETs use bidirectional links for data transmission. Unidirectional links are however more general in radio networks because they are more reliable than bidirectional links. Unidirectional links offer two opposite ways one for request and the other for reply while the bidirectional links use the same link for both request and reply operations.

- **Multiple routes**: this property has to reduce the number of reactions to changes of topology. Multiple routes property improves QoS, especially for multimedia applications in MANETs. It maximises the reliability of routes that are used for data transmission and improves the load balance among different nodes involved by the set of paths selected for data transmission.

- **Power conservation**: the nodes in MANETs are powered by batteries which are very limited in power and therefore, it may be useful to use a sort of stand-by mode to save power in mobile nodes.

- **Quality of Service support**: a routing protocol in MANETs may essentially incorporate a sort of QoS to support multimedia applications. Large number of users, user mobility, and frequently changing topology make a big challenge for an ad hoc routing protocol to support QoS.

- **The scalability of the protocol with network size:** the size of a MANET may be quite large in many applications such as communications in battlefields and disaster emergency operations. As there is no fixed infrastructure, the same bandwidth is used to find and maintain routes as well as to transmit data. As the size of the network grows, the amount of information maintained by each node in a MANET grows exponentially leading to increase routing control overhead dramatically [45].

- **Frequent topological changes:** The topology of a MANET may change rapidly in unpredictable time. When the current primary route is broken, a new one must be re-established.

Up to now, none of the proposed protocols for MANETs has all the above properties [46] however, the protocols are still under development and are probably extended with more functionality and more enhanced performance.

Generally, routing involves two basic activities, determining optimal routing paths and transporting information groups (packets) through a network. Despite this fact, finding the optimal route is not yet a crucial function of an ad hoc routing protocol and the primary function is still to find a route to the destination.

The major requirements of designing an efficient routing protocol in MANETs are summarised as follows:

- Minimum route acquisition

- Route reconfiguration in very short time

- Loop-free routing

- Distributed routing approach

- Minimum control overhead
- Scalability
- QoS provisioning
- Real-time traffic support
- Security and privacy

2.8.3 Conventional routing protocols

Routing protocols in conventional wired networks are usually based on either distance vector or link state routing protocols. Both of these protocols require periodic routing advertisements to be broadcast by each router. The question is: why not use a conventional routing protocol like link state or distance vector for MANETs? Even though the conventional routing protocols are well tested and most computer communications' people are familiar with them, the main problem with link state and distance vector is that they are designed for a static topology, which means that they would have problems of convergence to a steady state in a MANET with a very frequently changing topology. Link state and distance vector would probably work very well in a MANET in low mobility scenarios.

Because many of the proposed ad hoc routing protocols have a traditional routing protocol as underlying algorithm, it is necessary to understand the basic operation of conventional protocols like link state, distance vector, and source routing. These three conventional protocols can be explained briefly as follows:

- **Link State Routing** means that each node maintains a view of the complete topology with a cost for each link. To keep these costs consistent, each node periodically broadcasts the link costs of its outgoing links to all other nodes using flooding. On receiving this information by a node, it updates its view of the network and applies a shortest path algorithm to choose the next hop for each destination.

- **Distance Vector Routing** means that each node only monitors the costs of its outgoing links, but instead of broadcasting this information to all nodes, it periodically broadcasts to its neighbour an estimate of the shortest distance to every other node in the network. The receiving nodes then use this information to recalculate the routing tables by using a shortest path algorithm.

- **Source Routing** means that each packet must carry the complete path that takes the packet to the destination. Therefore, the routing decision is made at the source node. The advantage of this approach is that it is easy to avoid routing loops while the disadvantage is that each packet requires individual overhead.

2.8.4 Classification of routing protocols in MANETs

Many routing protocols have been proposed so far for MANETs, each one offering some advantage over the other approaches. However, the properties mentioned in subsection 2.10.2 are generally common desirable and each routing protocol designed for a MANET should possess.

Routing protocols in MANETs are classified into three types, proactive (table-driven), reactive (on-demand), and hybrid protocols [2][3][41][47].

Proactive, reactive and hybrid routing protocols:

Proactive protocols update periodically routing information to various nodes in the network so that a source node can find the route to the destination whenever needed. As the route is always known, forwarding packets is faster in proactive protocols [3][48]. The main disadvantage of such protocols is the large overheads of route discovery process which is launched periodically. Also, more bandwidth and power are consumed for updating process in proactive protocols [41]. Destination Sequenced Distance Vector (DSDV) [49] and Wireless Routing Protocol (WRP) [50] are examples of proactive routing protocols in MANETs. Proactive protocols characteristics are summarised as follows:

- Use table driven mechanism.
- Continuously evaluate routes.
- No latency in route discovery.
- Need a large capacity to keep network information updated.
- A lot of routing information may never be used.
- Route is determined based on the metric of small delay.
- Use significant wireless resources.

In reactive protocols, the optimal route is discovered on-demand and selected among multiple detected routes. As the route detected when needed and no updating overhead occurs, reactive protocols have smaller overheads of route discovery process than proactive protocols. Furthermore, less bandwidth and power are consumed in reactive protocols. More delay time may be spent to receive RREP packets of route discovery [3][48]. DSR, AODV, and TORA are examples of reactive routing protocols in MANETs. Reactive protocols characteristics are summarised as follows:

- Use route discovery mechanism by global search.
- More latency of route discovery.
- May not be appropriate for real-time communication.
- Evaluate route on-demand.
- End-to-end delay is significant.
- Route is usually determined based on the metric of minimum hop count.
- Avoid wastage of resources.

Hybrid routing protocols in MANETs combine between both proactive and reactive mechanisms. An example of hybrid protocols in MANETs is Zone Routing Protocol (ZRP) [51].

Location-based routing protocols:

In addition to proactive, reactive, and hybrid, there is a fourth type of ad hoc routing protocols includes location-based routing protocols which claim that no routing tables need to be maintained, and thus no overhead due to RDP and RMP is imposed. However, they need to obtain position data of their corresponding destinations either by an internal discovery process or by an independent position service (e.g. Global Positioning System - GPS), which will then impose overhead to maintain the position information either proactively or reactively. In location-based routing protocols, three location components can be used in both route discovery and packet forwarding, the position relationship between an intermediate node (a packet-forwarding node) and the destination, together with the node mobility [6]. An example of location-based routing protocols is Location-Aided Routing protocol (LAR) [52]. Based on the mechanism used for routing, most of position-based protocols can be also classified as proactive, reactive, or hybrid routing protocols (e.g. LAR is considered a reactive [53]). Thus, the first three types are still considered the typical types of ad hoc routing protocols.

Hierarchical routing protocols:

All routing protocols mentioned above as examples of proactive and reactive routing have flat structure because they use a flat network topology. A hierarchical routing protocol is a protocol that uses a hierarchical network topology.

As mentioned earlier in this chapter, the nodes in the network are dynamically organised into partitions called clusters and then, the clusters are aggregated again into larger partitions called super-clusters and so on. The centralisation associated with this type of routing protocol in MANETs enhances routing reliability and security.

Based on the mechanism of routing in the cluster itself and between different clusters, most position-based protocols can be also classified as proactive, reactive, or hybrid routing protocols. An example of such protocols is the Cluster-head Getaway Switch Routing protocol (CGSR) [54] which is a proactive routing protocol uses a hierarchical network topology.

Single path vs. multipath protocols:

Single path abstraction in routing protocols means that multiple routes can be detected due to routing discovery process and one route of them (usually the optimal) is maintained in the source node routing table. DSDV and AODV are examples of single path routing protocols. In multipath routing protocols, multiple routes can be detected due to routing discovery process and all routes are maintained in a source node routing table. All of these routes can be utilised for data transmission between the source and the destination nodes. DSR and TORA are examples of multipath routing protocols. There are several criteria can be used for comparing single path,

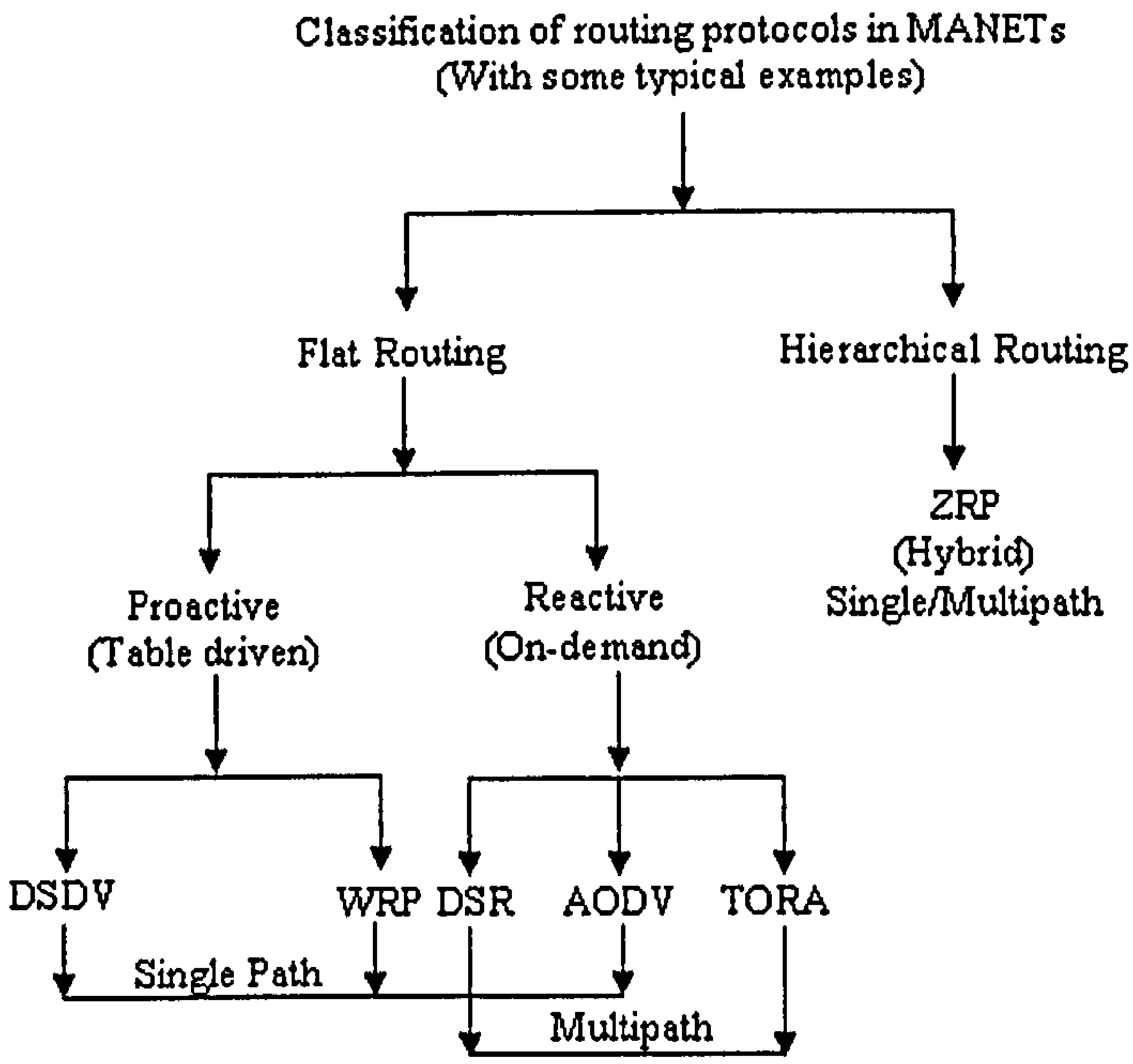

Figure 2.7: Classification of routing protocols in MANETs with some examples

and multipath routing in MANETs. The first is the overhead of route discovery in multipath routing which is expected to be much more than that of single path routing. On the other hand, the frequency of route discovery which is expected to be much less in a network which uses multipath routing, since the system can still operate even if one or a few of the multiple paths between a source and destination fail (these expectations are mentioned in some literatures as facts however, they are tested, verified and evaluated for single path against multipath protocols later in Chapter 3). The second criterion is throughput; it is commonly believed that using multipath routing results in a higher throughput. The reason is that all nodes are assumed to have a fixed and limited capacity which is represented by bandwidth and processing power. Since multipath routing balances the load better, the overall throughput would be higher in multipath comparing to single path routing [40][55]. Throughput along with other criteria such as packet delivery fraction and average end-to-end delay are also tested, verified, and evaluated for single path against multipath protocols later in Chapter 3. The four criteria mentioned above are defined later in Chapter 3 as performance metrics of the simulation process of ad hoc routing protocols.

Figure 2.7 shows a 4-level classification of routing protocols in MANETs with some examples of proactive, reactive, hybrid, single path and multipath protocols.

2.8.5 Proactive Routing Protocols

Proactive protocols update periodically routing information to various nodes in the network so that a source node can find the route to the destination whenever needed. As the route is always known, forwarding packets is faster in proactive protocols. The main disadvantage of proactive protocols is the large overheads of the route discovery process which is invoked periodically. Additionally, more bandwidth and power are consumed for updating process in proactive protocols [41]. DSDV and WRP are examples of traditional proactive routing protocols in MANETs [47].

DSDV:

DSDV [49] is a flat (non hierarchical) and proactive routing protocol which means that routes to all destinations are readily available at every node at all times. It is considered a distributed routing protocol because it is an enhanced version of the distributed Bellman-Ford algorithm [57][58]. In DSDV, every node maintains a routing table that contains next-hop entry and the number of hops needed for all reachable destinations. DSDV uses the abstractions of single path and bidirectional links, and thus DSDV does not support a unidirectional link. In DSDV, nodes broadcast a periodical route advertisement frequently to maintain routing information within a network. Routing table entries are involved in the route advertisements. On receiving a route advertisement, a nodes routing table is updated. Sequence numbers are used for optimal route selection so that the optimal route is the route that has greater sequence number. Hop count is the next criteria of optimality so that a route with lower hop count is chosen if the sequence numbers are equal.

An Example that explains the process of sending packet from a source node (node 1) to a destination node (node 13) is shown in Figure 2.8. It is clear from the figure that the optimal path which is updated proactively is the path $1 \longrightarrow 2 \longrightarrow 4 \longrightarrow 12 \longrightarrow 13$.

Another Example that explains the process of broken link is shown in Figure 2.9. Based on this example, the route maintenance process of DSDV is summarised as follows:

- Node 12 is the old next node of node 4 before updating its routing table.
- Node 8 is the new next node of node 4 after updating its routing table.
- Routing table of node 8 is also updated.
- Both routing tables of node 4 and node 8 are updated also with a new sequence number greater than the old one for node 8 itself (the destinations of node 4) and node 12 (the destinations of node 8).

DSDV protocol has the following major advantages:

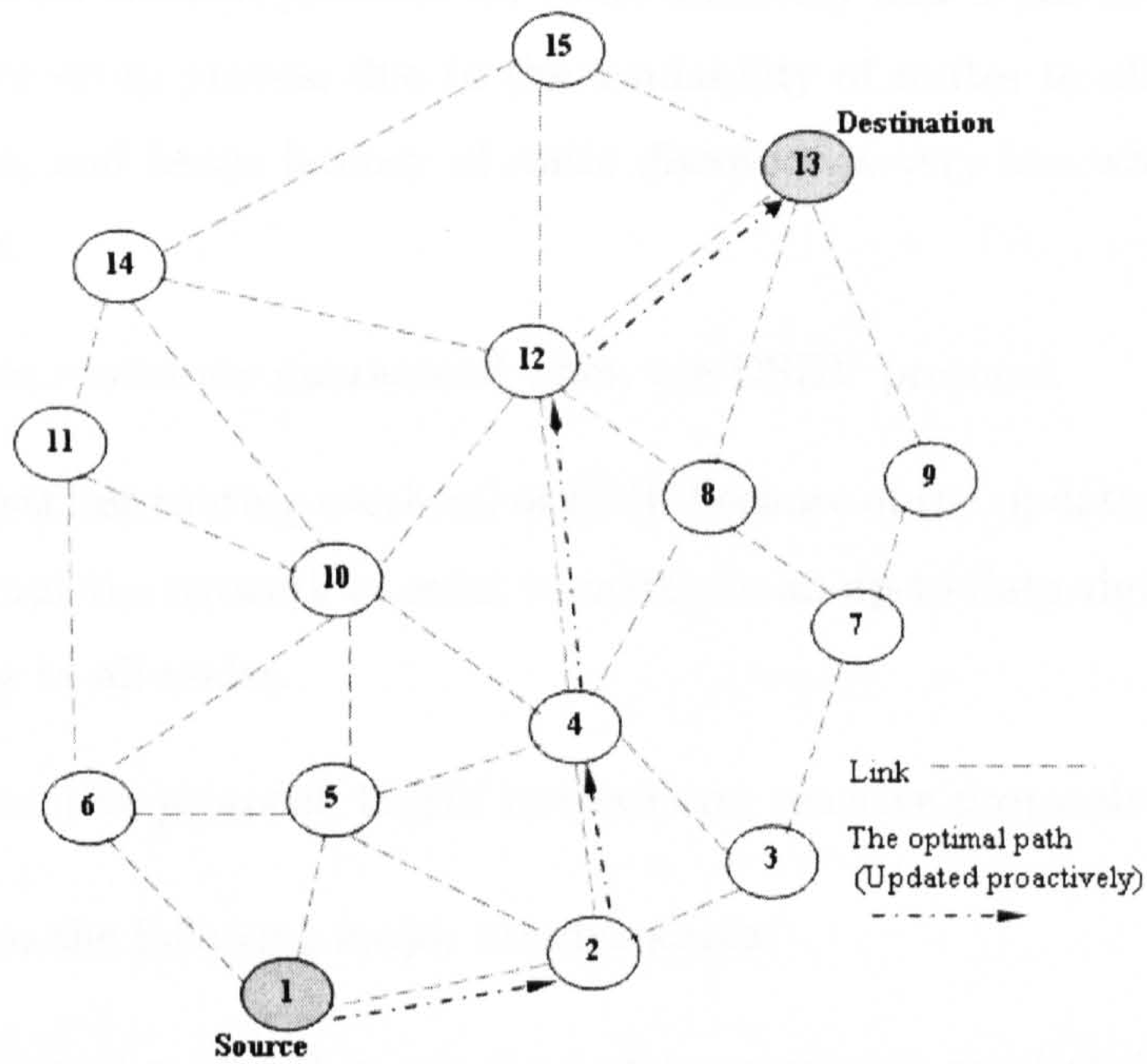

Figure 2.8: Route establishment in DSDV

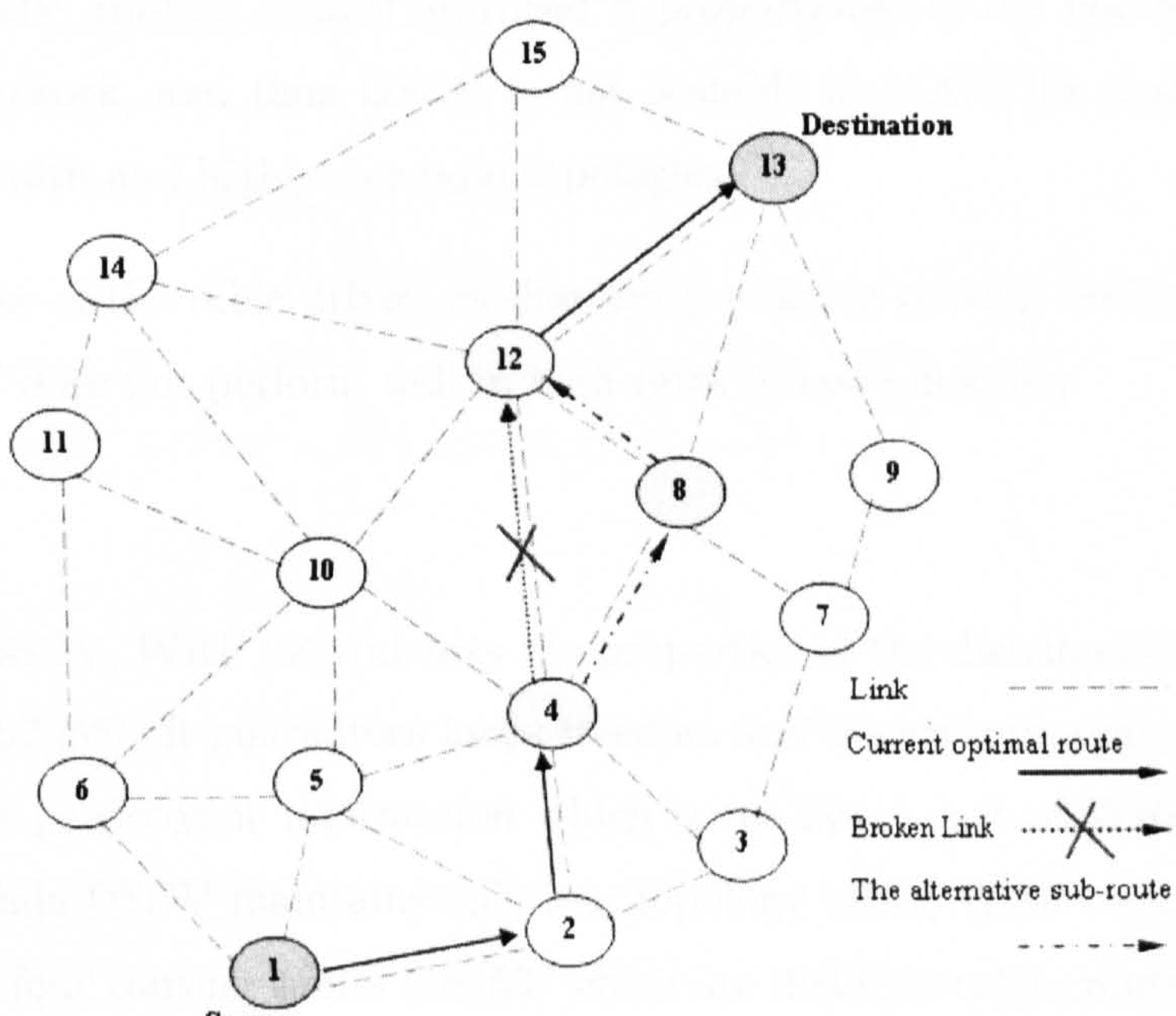

Figure 2.9: Route maintenance in DSDV

- DSDV is an efficient protocol for route discovery and it has much less delay in the route setup process due to the availability of routes to all destinations at all times, and hence latency of route discovery is very low when using DSDV protocol.
- Loop-free routes are guaranteed when use DSDV protocol.
- DSDV has less routing overhead of RMP because of the updates are propagated throughout the network in order to maintain an up-to-date view of the network topology at all nodes.
- As a proactive protocol, DSDV outperforms reactive protocols in low mobility.

DSDV has also the following major disadvantages:

- Heavy control overhead due to the updates needed at any link failure, especially in high mobility scenarios.
- In DSDV, routing control overhead is proportional to the number of nodes in the network, and thus DSDV is not scalable in MANETs that have limited bandwidth and highly dynamic topologies.
- Because of the table-driven mechanism (updating routing tables periodically), DSDV does not perform well in high rates of node mobility.

WRP:

Similar to DSDV, WRP [50] inherits the properties of the distributed Bellman-Ford Algorithm [57][58]. It guarantees loops freedom and avoids temporary routing loops by using the predecessor information which is the novel part of WRP protocol [2]. However, while DSDV maintains only one topology table, WRP requires each node to maintain four routing tables [48][53] which are distance table, routing table, link-cost table, and message retransmission list table [2]. Distance table contains the network view of the neighbours of a node matrix where each element contains the distance and the last hop node reported by a neighbours for a particular destination. Routing table contains the up-to-date view of the network for all known destination. It keeps the shortest distance, the next hop, the last hop (the next node to reach the destination), and a flag indicating the status of the path. The path status may be correct (a simple path), or error (a loop), or null (the destination node not marked). Link-cost table contains the number of update periods and the cost (e.g. the number of hops to reach the destination) of relaying message through each link (e.g. for a broken link, the cost is ∞). Finally, message retransmission list table contains an entry for every update message that is to be retransmitted and maintains a counter for each entry [50].

Link changes are propagated using update messages sent between neighbouring nodes. Hello messages are periodically exchanged between neighbours. A node does not only update the distance for transmitted neighbours but also checks the other neighbours distance, hence convergence in WRP is much faster than DSDV.

In addition to the same advantages of DSDV, WRP has faster convergence, involves fewer table updates, eliminates looping situations in a better way, and checks the consistency of all neighbours every time [2][53][59]. On the other hand, WRP has two main disadvantages; the first is related to consuming a significant amount of memory due to maintaining four tables. The second is that WRP is not suitable for highly dynamic and very large MANETs due to the routing control overhead involved in updating table entries at high mobility scenarios [2][53].

2.8.6 Reactive Routing Protocols

In reactive protocols, the optimal route should be discovered on-demand and selected among multiple detected routes. As the route detected and no updating overhead occurs, reactive protocols have smaller overheads of route discovery than proactive protocols. Thus, less bandwidth and power are consumed in reactive protocols. In reactive protocols, less delay time may be spent to receive RREPs of RDP. DSR, AODV, and TORA are examples of traditional reactive protocols in MANETs [1][14].

DSR:

DSR [15] is a flat and fully reactive routing protocol which means the route is detected when needed and no updating overhead occurs. It is also considered a distributed and multipath routing protocol. DSR is a source routing protocol which means that an ordered list of all routes used by a packet sent between a source and any intermediate node (or the destination itself) are maintained in the packet header. Each node in the network maintains a route cache in which all routes used frequently to any given node are stored. Since it is a reactive protocol, DSR uses on-demand route discovery mechanism by flooding RREQ packets through the network nodes. Each intermediate node looks for the required route in its route cache and if the route is found, the node replies a RREP packet back to the source node using the source route maintained in the RREQ packet. If the required route is not found, the intermediate node forwards the RREQ to all neighbours and so on until reaching the destination node. The destination node replies back to the source node a RREP packet for each RREQ packet received. Each RREP is replied using the source route maintained in the corresponding RREQ packet. Each RREP received by the source represents an independent path to the destination. All these multiple routes are maintained in the routing table of the source node, and thus DSR is considered a multipath protocol. Finally, DSR uses route maintenance mechanism in the case of link failures.

Because of DSR is a source routing protocol, it is resistant to the presence of routing loops. Any intermediate node can detect a loop by comparing its own address with the sequence hop list in the header of the RREQ packet. Existence of a fresh route to the destination in the route cache of any intermediate node may assist in stopping RREQ flooding through the rest of nodes in the network by sending back a RREP early. Furthermore, routes to the destination can be learned and recorded by intermediate nodes while forwarding the RREP packets [60].

Figure 2.10 and Figure 2.11 illustrate examples of route request and route reply in DSR protocol. As shown in Figure 2.10, each RREQ packet maintains a list of all routes to the source node. This is because DSR is a source routing protocol. The destination uses the source routes to send RREPs to the source node as shown in Figure 2.11.

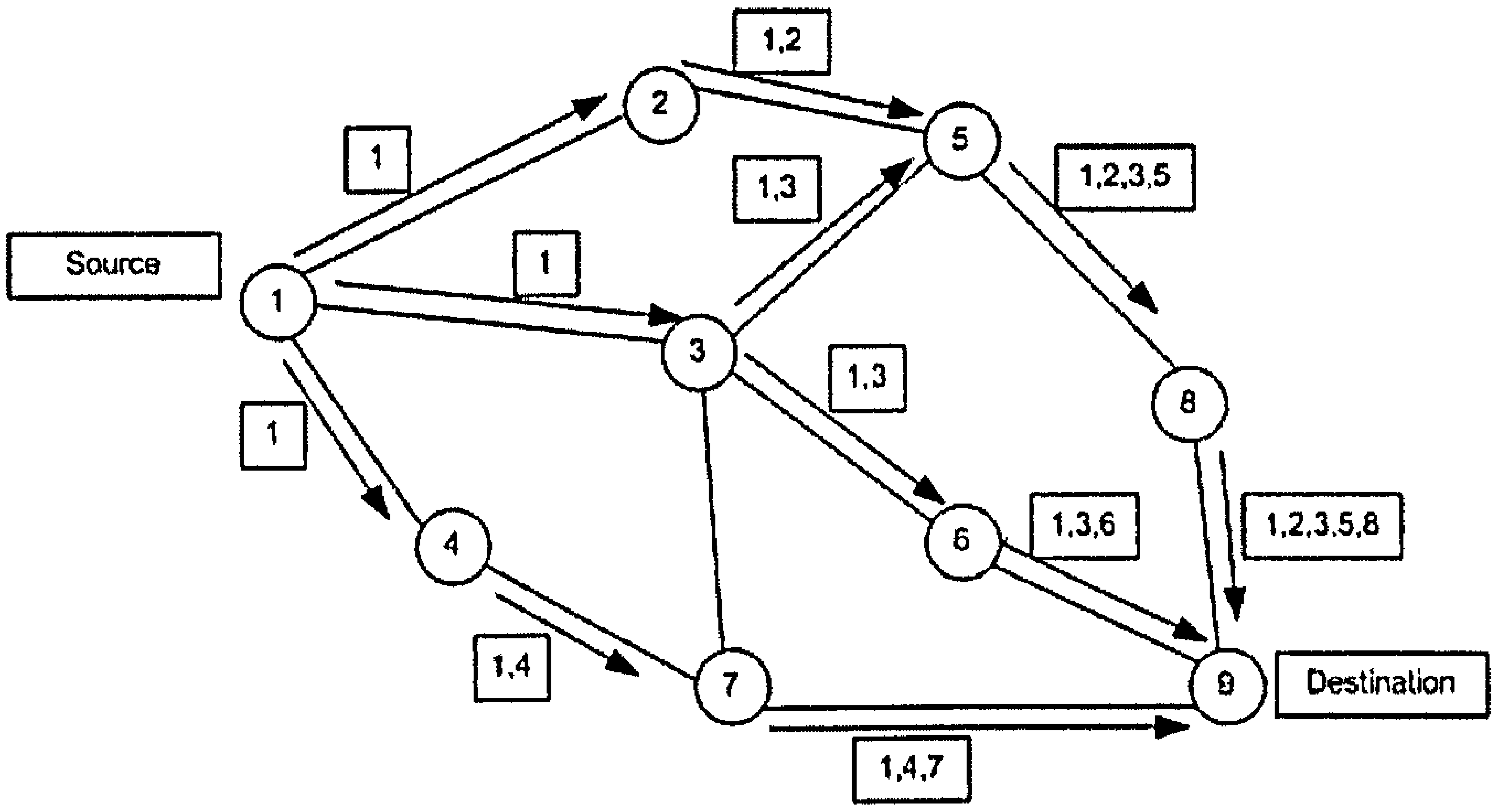

Figure 2.10: Route request in DSR route discovery

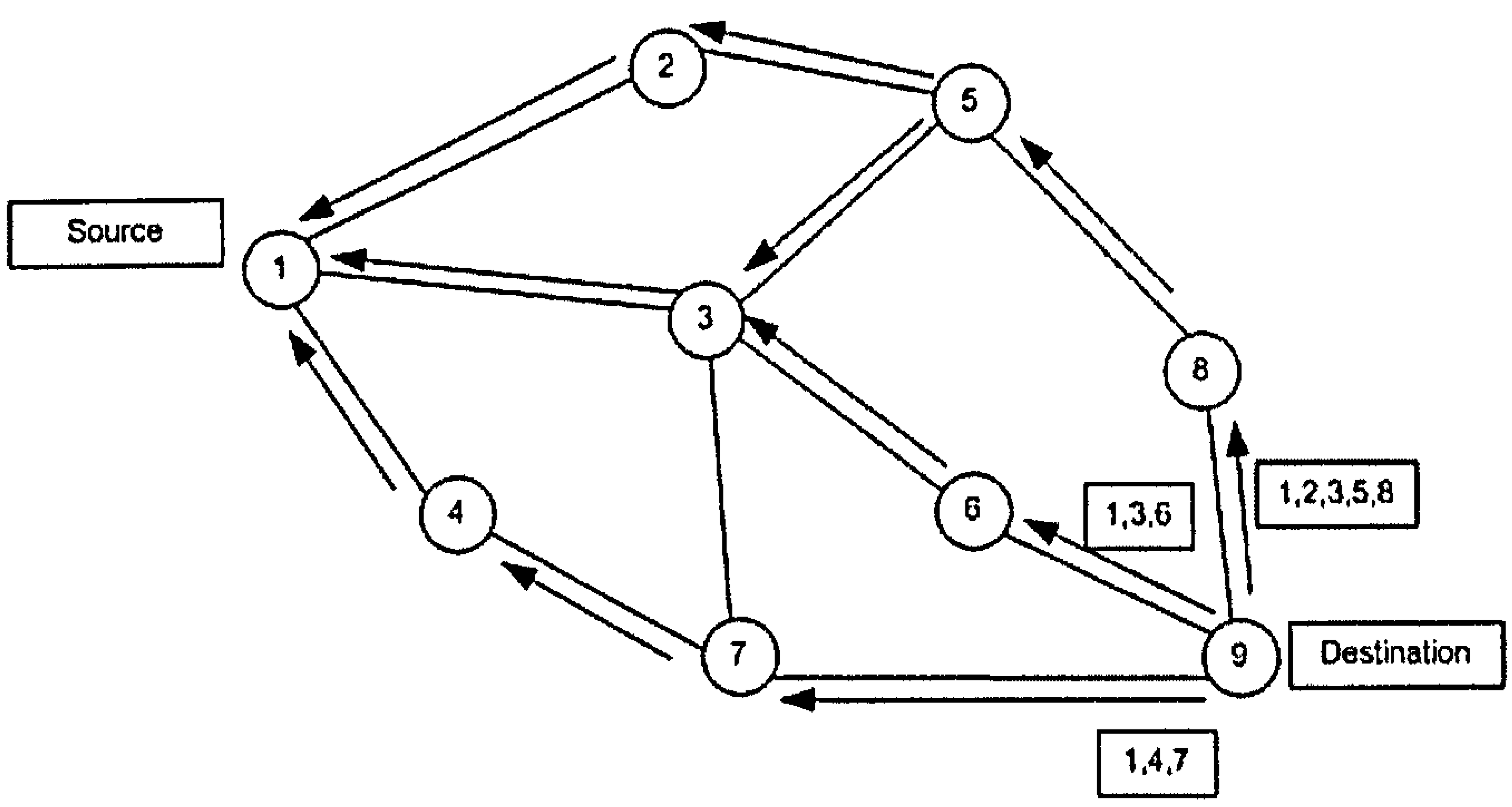

Figure 2.11: Route reply in DSR route discovery

An example of route maintenance in DSR is the situation illustrated in Figure 2.12. When detecting a link failure such as the link between node 8 and node 9, a RERR packet is generated from the node adjacent to the broken link (node 8) to inform the source node (node 1) using the source route $5 \longrightarrow 3 \longrightarrow 2 \longrightarrow 1$. In this case, the source node reinitiates the route establishment procedure to detect an alternative route. The cached entries related to the failed route at the intermediate nodes (nodes 3, 5) and the source node are removed when a RERR packet is received.

DSR protocol has the following major advantages which are almost verified and

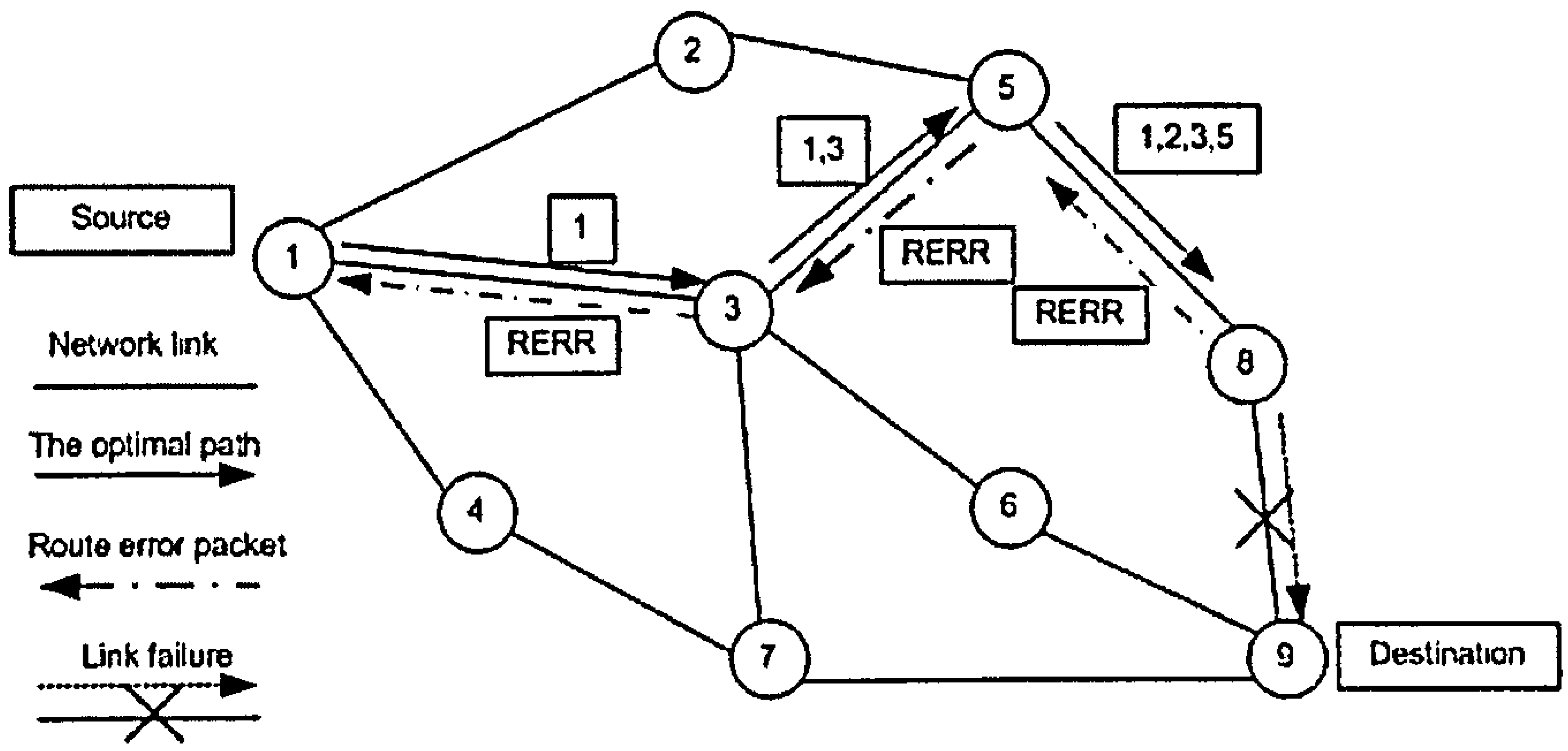

Figure 2.12: Route maintenance in DSR

evaluated later in Chapter 3:

- Less routing control overhead because this protocol is a reactive approach which eliminates the need to periodically flood the network with table update messages.
- A route to a destination node is established only when it is required, and thus no need to find routes to all other nodes in the network.
- Routing control overhead is also reduced by the intermediate nodes that utilise the route cache information without need to forward RREQ packets in the case of a fresh route to the destination is found.

DSR has also the following major disadvantages:

- Because of DSR is a source routing protocol, packet header grows with route length. This consequently increases routing control overhead (larger size of routing packets) and routing delay overhead.

- Because of the concept of route cache and multipath abstraction, applying DSR leads to consume a lot of network resources such as the memory and computing time.
- DSR performance is decreased when several simultaneous route requests initiated and when many route replies due to caching. This consequently increases routing delay overhead.

AODV:

AODV [12] is a reactive, flat, single path, and distributed routing protocol designed for MANETs. Unlike proactive protocols, which maintain updated information about all routes related to each node in its routing table, AODV builds routes between a source and destination only on-demand of source nodes, and thus it does not require mobile nodes to maintain routes to destinations that are not communicating [8].

Unlike DSR, AODV is not a source routing protocol meaning that a packet does not maintain a list of all routes to the source node. Instead, AODV deals only with neighbours of the first hop to forward a RREQ or reply RREPs. In AODV, routing table stores information about the next hop to the destination and a sequence number to guarantee loop-free routes [61].

Based on AODV mechanism, one route entry (usually the optimal route) is maintained in the routing table of each node to each destination that the node is communicating with in the network. This feature is called single route abstraction in AODV [45]. When a source wants to send a data packet to a destination, supposed that no valid entry for that destination is in its routing table, it floods a RREQ packet to all first hop neighbours in the network. A RREQ packet contains source identifier, destination identifier, source sequence number, destination sequence number, broadcast identifier, time to live field, and a hop count. A RREQ is flooded by forwarding it to the whole network until the destination is reached from different routes. The destination node keeps track all detected routes and then sends back RREPs in a backward process until the source node is reached using all routes established in the

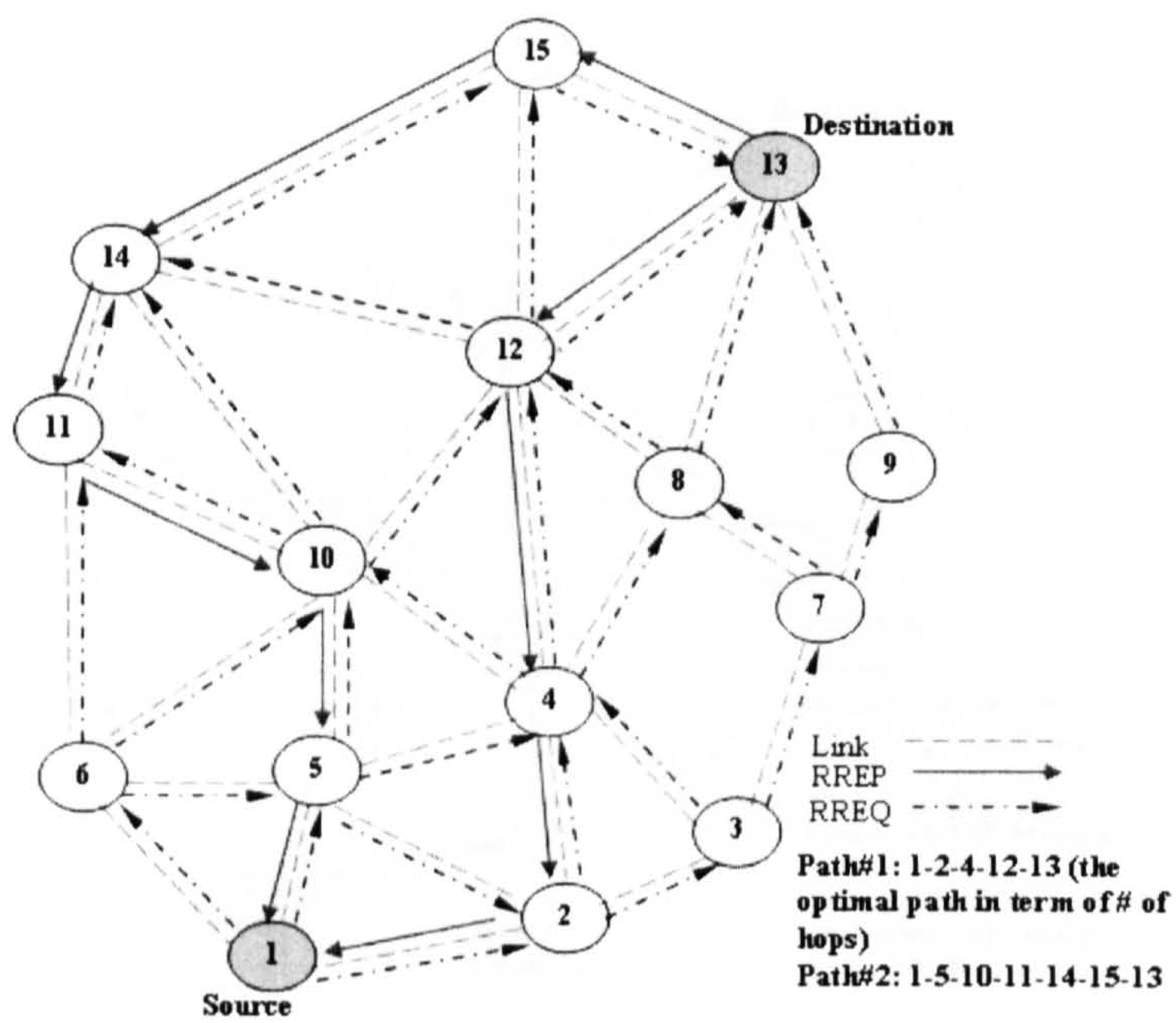

Figure 2.13: Route establishment in AODV

forward process. On receiving a RREP packet by an intermediate node, hop count is incremented and the routing table entry is updated [22][53].

AODV uses error messages for route maintenance. When a node detects a broken link to the next hop, it generates a RERR message that contains a list of unreachable destinations and sends it to corresponding nodes. The source node should re-establish a new RDP to detect an alternative route to the destination [1].

Figure 2.13 demonstrates an example that explains the process of sending a RREQ from source node 1 to destination node 13, and sending back a RREP to the source node using AODV protocol. An example that explains the route maintenance process in AODV protocol is illustrated in Figure 2.14.

AODV protocol has the following major advantages which are almost verified and evaluated later in Chapter 3:

- Less routing control overhead because routes are established on-demand.
- The latest route to the destination can be found out using the destination

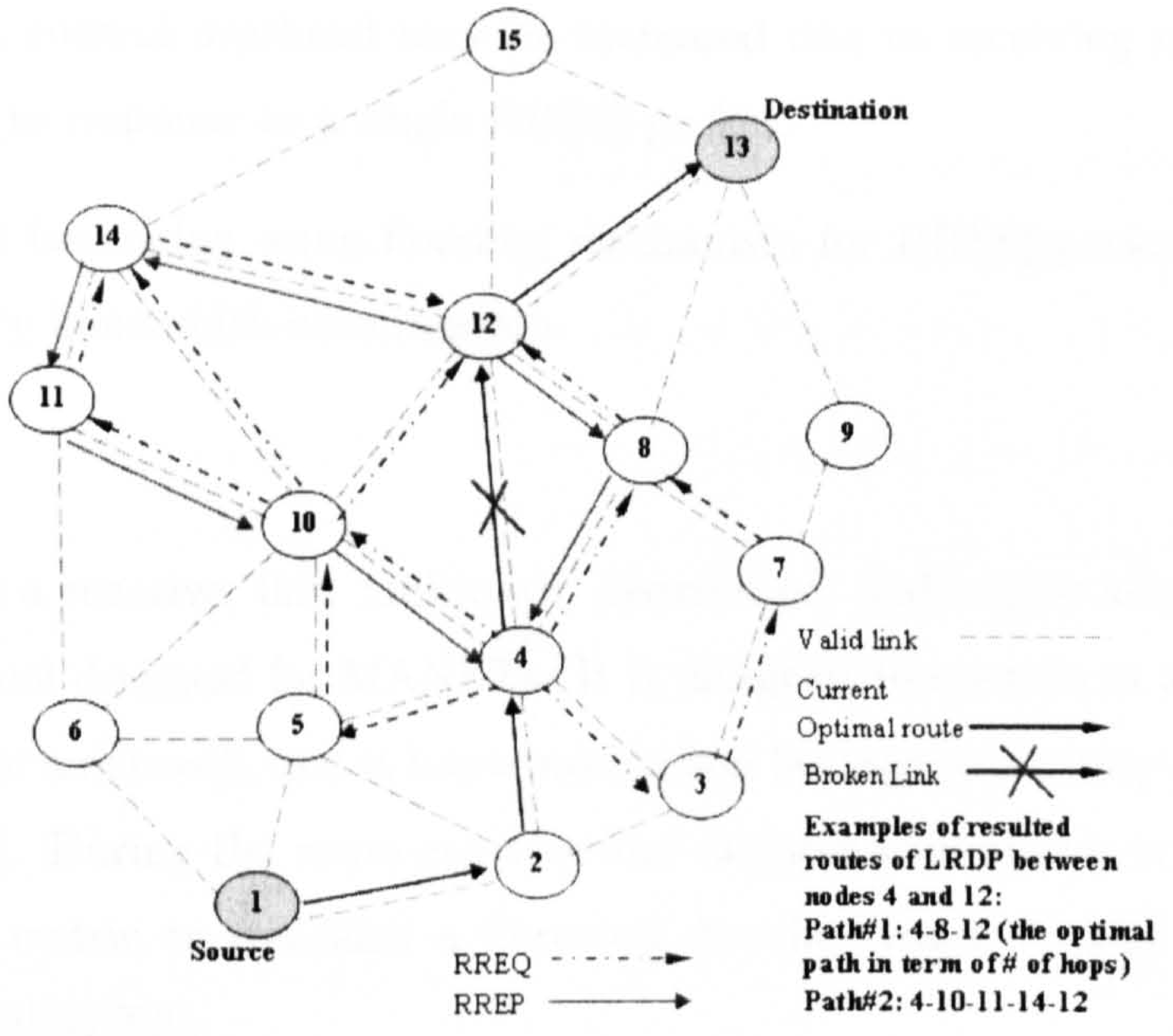

Figure 2.14: Route maintenance in AODV

sequence numbers associated with the RREQ and RREP packets.

- The connection setup delay is less because no route-status update from any intermediate node is needed.

AODV has also the following major disadvantages which are verified and evaluated later in Chapter 3:

- The intermediate nodes can lead to inconsistent information of the routes which consequently leads to detect some invalid routes. Because of AODV is a single path protocol, this drawback cannot be considered a vital problem if the optimal route is not one of these routes.

- Stale entries can be found if the source sequence number is very old and the intermediate nodes have a higher but not the latest destination sequence number. This consequently leads to detect some invalid routes as discussed above in the previous drawback.

- Routing control overhead may be increased due to receiving multiple RREP packets in response to a single RREQ packet.
- Periodic beaconing using flooding mechanism for RREQ packets leads to unnecessary bandwidth consumption.

TORA:

TORA [16] is a reactive, flat, multipath, distributed, and highly adaptive loop-free routing protocol designed for MANETs. It is designed to operate in a high mobility environment of a network, and it has a mechanism belongs to a family of link reversal algorithm [22]. During the route creation and maintenance phases in TORA, nodes use a height metric to establish a Directed Acyclic Graph (DAG) rooted at the destination [48][53][62].

A routing path moving direction, speed, and transmission range are monitored to predict if a route failure is found by DAG. Timing is an important factor for TORA because the height metric is dependent on the logical time of a link failure. TORA assumes that all nodes have synchronised clocks which can be accomplished via an external time source such as GPS [2].

The idea behind TORA is taking into account the status of the communication links between nodes which is related to the variability in mobility and network topology. Based on this idea, TORA is designed to resist the variability of network topology due to many considerations such as mobility and power considerations. The key design concept of TORA is to use control messages in a small set of nodes near the potential change of topology. Each node in this set of nodes maintains routing information about the first hop neighbours. TORA utilises some sort of route maintenance process to repair link failures that usually occur in the network [7][8][63]. TORA has three main functions:

- Establishing routes: the process of creating routes (multiple routes) which consists of determining a sequence of links that are directed for each path connects between the source and the destination.

- Maintaining routes: the repairing process which is a reaction to topology changes. When a primary route gets broken down, this process is invoked to re-establish alternative routes (multiple routes) within a finite time.

- Erasing routes: when a partition is detected in the network, all invalid routes must be removed from the network. This is done by making directed routes undirected.

TORA has the following major advantages which are almost verified and evaluated later in Chapter 3:

- A reactive and source initiated routing protocol. As mentioned earlier in DSR protocol, these properties are considered advantages.

- Uses an artificial intelligence approach which reduces the route discovery overhead.

- Less routing control overhead because TORA limits the control packets for route reconfigurations to a small region.

- A multipath protocol which mitigates congestion.

- Creates loop-free routes.

- Handles partitions by erasing invalid routes.

TORA has also the following major disadvantages which are almost verified and evaluated later in Chapter 3:

- Using an artificial intelligence approach in TORA is also considered a disadvantage from the perspective of the implementation complexity.

- The local reconfiguration of paths in TORA results in non-optimal routes which consequently lead to increase routing delay overhead.

2.8.7 Hybrid Routing Protocols

A hybrid routing protocol in MANETs is a combination between a reactive and proactive protocols. A very common example of hybrid protocols in MANETs is ZRP [51] which combines the best features of both proactive and reactive routing protocols. ZRP proactively maintains routes within a local region of the network which is called the routing zone. The information of the routing zone topology is utilised by ZRP to improve the efficiency of a reactive route query/reply mechanism. ZRP can be configured for a particular network by a single parameter adjustment which is the routing zone radius.

The key concept employed in this protocol is to use a scheme of a proactive routing protocol called Intra-zone Routing Protocol (IARP) within a local routing zone in the r-hop neighbourhood of every node, and use a scheme of a reactive routing protocol called Inter-zone Routing Protocol (IERP) for nodes beyond this zone.

The routing zone of a given node is a subset of the network. Each node exchanges periodic route update packets to maintain the information about routes to all nodes within its routing zone. The IERP is responsible for finding paths to the nodes which are not within the routing zone. IERP uses the routing information available at every node's routing zone. ZRP protocol has the following major advantages:

- Combines the best features of both proactive and reactive routing protocols.
- Reduces the routing control overhead compared to both traditional reactive and proactive protocols which have the disadvantages of using the RREQ flooding mechanism and periodic flooding of routing information packets respectively.

ZRP has also the following major disadvantages:

- Higher routing control overhead is produced in the absence of a query control, especially if there is a large overlapping between routing zones of the nodes.
- The query control must ensure that the duplicated RREQs are not forwarded to the neighbours.

Finally, it may be useful to summarise the most significant differences between the four typical proactive and reactive routing protocols in MANETs, namely DSDV, DSR, AODV, and TORA which are evaluated based on the simulation presented in Section 3.6. The differences are summarised in Table 2.2.

Table 2.2: Comparison of typical proactive and reactive ad hoc routing protocols

Comparison Aspect	DSDV	AODV	DSR	TORA
Routing Form (Flat/hierarchical)	Flat	Flat	Flat	Flat
Routing Mechanism	Table-driven	On-demand	On-demand	On-demand
Loop Free Routes	Yes	Yes	Yes	Yes
Multipath Abstraction	No	No	Yes	Yes
Distributed	Yes	Yes	Yes	Yes
Route Maintenance Support	No	No	Yes	Yes
Unidirectional Link Support	No	No	Yes	Yes
QoS Support	No	No	No	No
Capability of Applying Security Techniques	No	No	No	Possible
Route cache strategy	No	No	Yes	No
Power-aware	No	No	No	No
Routing Metric(s)	Greater sequence number, and less hop count	most recent and shortest path	shortest path	shortest path

2.9 Multipath Routing in MANETs

Multipath routing concept is a new trend addressed in so many efficient routing protocol extensions in MANETs. Multipath abstraction is considered an advantage due to easy recovery from a route failure, and thus multipath protocols are considered more reliable and robust [9]. Also, multipath routing can save energy, reduce frequent routing update, enhance data transmission rates, and increase wireless network bandwidth [18]. In a broad sense, multipath routing enables route reliability and facilitates load balancing. These two advantages are commonly used in several applications, especially in routing fault tolerance and QoS provisioning for heavy multimedia and real-time traffic.

Single path routing is a feature associated with many traditional routing protocols in MANETs. It means that the optimal route only is maintained in the source node routing table even multiple routes can be detected during a routing discovery process. As mentioned earlier in this chapter, AODV in addition to many other protocols such as DSDV and WRP are examples of single path protocols.

In contrast with single path, multipath protocols maintain all routes that can be detected due to a routing discovery process in the source node routing table. All detected routes can be used sequentially (e.g. as backup routes) or cooperatively (e.g. for load balancing) for data transmission process between a source and destination nodes. In multipath protocols, a source can select the optimal route among multiple available routes, which enhances the route availability and consequently minimises frequent re-establishing of RDP.

This section presents a review of state-of-the-art multipath routing in MANETs covering applications, classification, and design issues of multipath routing in MANETs. A novel aspect of this review is that multipath routing protocols in MANETs are classified into new four paradigms. This classification is figured out based on analyzing the most significant aspects and properties of multipath routing in MANETs.

2.9.1 Historical background

Multipath routing concept between a source and destination nodes is proved in wired networks either voice networks or data networks [80][81][82][83]. The general using of multipath routing is related to cooperating and balancing loads. Instead of using a single path, the data flow is divided among a number of paths which leads to a better balancing of load and energy throughout the network [55].

As an example of using multipath routing in voice networks, traditional circuit switched telephone networks used a set of paths for each pair of source and destination nodes. This type of multipath routing is called alternative path routing. Each set of paths consists of a primary path and one or more alternative paths. An alternative path can be used when the primary path fails.

Multipath routing is also used in data networks to support QoS using connection-oriented service. Standard Private Network-to-Network Interface (PNNI) in Asynchronous Transfer Mode (ATM) networks uses a set of paths between each pair of source and destination nodes [84]. As a backup, the alternative path is used when the primary optimal path fails.

In the context of MANETs, multipath routing is proposed in both the early reactive and hybrid routing protocols such as DSR, TORA, ZRP, and the Optimised Link-State Routing protocol (OLSR) [85]. The same idea of route backup is utilised in MANETs meaning that the alternative path is used when the primary optimal path fails.

Multipath routing consists of three components route discovery, route maintenance, and traffic allocation [11]. Only the first two components are considered in the scope of this thesis while the third component is out of scope of this thesis. This is because the first two components represent the routing process which is the main scope of this thesis while traffic allocation component concerns the data transmission process which deals with distributing data among the set of routes assigned to a session between a source and destination nodes.

2.9.2 Applications of multipath routing in MANETs

Multipath routing is useful for several applications in MANETs, the following points summarise the most significant applications of multipath routing in MANETs:

- **Heavy multimedia and real-time traffic:** applications of this type are related to QoS issue in multipath routing. The most significant design issues of a QoS-aware multipath routing are congestion control and video transport over MANETs with path diversity [86]. Path diversity of video transport over

MANETs mainly focuses on how to distribute the video traffic among multiple paths [87].

- **Routing inprovement:** related to minimising routing overhead and end-to-end delay, and maximising the reliability of routes that are used for data transmission (i.e. maximising fault tolerance) [11][88].

- **Hybrid network reliability:** concerns the MANETs that may contain heterogeneous nodes, where some nodes are more reliable than the other nodes. The reliable nodes should not be deployed randomly, especially when the number of reliable nodes is small. The idea behind increasing reliability in hybrid networks is to look for different segments of multiple node-disjoint subroutes. The reliable path is formed by the concatenation of these reliable segments [89].

- **Diversity coding:** the idea behind using multipath in diversity coding is to improve the reliability of data packet transmission. A multipath traffic allocation scheme is introduced in [90] by splitting a packet into equal size blocks and then, an overhead is added to each block in the packet. On packet transmission, the total blocks are allocated among the multiple routes assigned for transmission process between the source and the destination nodes hopefully the probability of losing no more than the overhead blocks is maximised. Another approach that applies diversity coding is introduced in [87], in which multiple description coding is used to distribute video traffic over multiple paths in MANETs.

- **Load balancing:** concerns improving the load distribution among different nodes that are involved by the set of paths assigned to a session of data transmission between a source and destination nodes. The better the load balance the lower the resource consuming such as bandwidth, memory, and energy consuming, and additionally the lower end-to-end delay overhead of routing and data transmission [88].

- **Energy consumption balancing:** which is a result of balancing the load among the multiple cooperative routes of a session between a source and destination nodes. Node-disjoint routes are expected to balance the load (and then the energy consumption) efficiently better than link-disjoint and non-disjoint routes [88].

- **Security strengthen of a link key in MANETs:** by establishing a multipath key reinforcement through multiple disjoint paths [35]. Node-disjoint and link-disjoint routes can be utilised to strengthen link security, while non-disjoint routes will increase the probability of security threats due to link sharing among different routes. Intrusive link/node is a serious threat of the information integrity, thus the higher the disjointness of multiple routes the lower the security threats of a link.

2.9.3 Classification of multipath routing protocols in MANETs

Multipath routing protocols in MANETs can be classified into four paradigms; classification based on a multipath goal, classification based on the basic type of a routing protocol, classification based on a multipath application, and finally classification based on routes disjointness type.

Classification based on a multipath goal:

Traffic allocation may be either centralised or distributed based on the goal of multipath routing. When traffic allocation is concentrated only on the optimal route, the other routes are considered as backup routes. This is usually applied to enhance the reliability of the routing algorithm. However, the goal of multipath routing may be determined to use all routes cooperatively to transmit data to the same destination, which is usually applied to balance heavy loads such as multimedia and real-time data. In this case traffic allocation is distributed. From the perspective of load balancing, data transmission load may be balanced among different routes or concentrated only on one route. Thus, multipath routing can be classified into two types based on a multipath goal:

- **Centralised traffic allocation multipath routing protocols:** in this type, multiple routes are used only for route reliability while data transmission is always accomplished using the optimal valid route. Thus, this type of multipath is considered a non-balanced-load multipath data transmission. Examples of this type are the approaches developed in [89], [91], [92], and [93].

- **Distributed traffic allocation multipath routing protocols:** in this type, all multiple routes assigned to the pair of source-destination nodes are used to balance a load for data transmission, and thus this type of multipath is considered a balanced-load multipath data transmission. Examples of this type are the approaches developed in [94], [95], [96], and [97].

It is worthy to mention that some literatures tried to prove the infeasibility of using multipath for load balancing in MANETs. Many simulation results in several literatures proved that even the common belief is that multipath routing balances the load significantly better than single path routing in wired networks; this is not essentially the case in MANETs. For example, the model proposed in [55] introduces a new model for evaluating the load balance under multipath routing which shows that unless using a very large number of paths, which is very costly, the load distribution is almost the same as single shortest path routing. However unlike these results, the framework proposed in [95] have concluded how the amount of overheads is affected by the number of multiple paths, and it shows in particular that when this number is more than three paths, the additional amount of overheads is significant. On the other hand, many literatures recommend using different numbers for a maximum number of paths without any clear justification. Thus, to consider the conclusions of the above two models as facts, both models need more evaluation and verification in different scenarios taking into consideration all parameters that may affect the performance of single path and multipath routing in MANETs.

Classification based on the basic type of a routing protocol:

Multipath abstraction is associated with different types of routing protocols regardless of the proactivity or reactivity feature of a routing protocol [2][88]. Thus, multipath routing can be classified into five types based on the basic type of a routing protocol in MANETs:

- **Proactive multipath routing protocols:** Most of proactive routing protocols in MANETs are proposed with the single path abstraction such as DSDV, WRP, and OLSR. However, there have been some multipath proactive protocols that are developed recently. Global State Routing (GSR) [98] and Fisheye State Routing (FSR) [99] are examples of multipath proactive routing protocols in MANETs.

- **Reactive multipath routing protocols:** The original DSR and TORA are well-known as multipath routing protocols in MANETs. Many extensions of these two protocols in addition to many extensions to the original AODV are also considered multipath routing protocols in MANETs.

- **Hybrid multipath routing protocols:** ZRP is a well-known multipath hybrid routing protocol in MANETs. Another multipath hybrid algorithm is called Ant Agents for Hybrid Multipath Routing in Mobile Ad Hoc Networks (AntHocNet) which is proposed in [100]. The route setup of this scheme is performed by reactive algorithm and the route probing and exploration are done by proactive scheme.

- **Hierarchical multipath routing protocols:** Most of hierarchical routing protocols in MANETs are proposed with the single path abstraction such as Cluster-head Getaway Switch Routing protocol (CGSR) [54] and Hierarchical State Routing (HSR) [101]. However, some recent protocols are considered multipath hierarchical routing protocols such as Zone-based Hierarchical Link State Routing Protocol (ZHLS) [102] (ZHLS can be multipath if more than one virtual link exists [53]).

- **Location-based multipath routing protocols:** LAR protocol is described in Section 2.8 as an example of single path location-based routing protocols in MANETs. A multipath routing version of LAR is called Multipath Location-Aided Routing (MLAR) which is proposed in [60]. MLAR uses position information (2D or 3D) to make routing decisions at each node.

Classification based on a multipath application:

There have been many recent multipath routing protocols in MANETs which can be considered as application-oriented protocols. Multipath routing protocols can be classified into four types based on the application type of multipath routing:

- QoS-aware multipath routing protocols.
- Fault-tolerance-aware multipath routing protocols.
- Energy-aware multipath routing protocols.
- Security-aware multipath routing protocols.

Multipath routing protocols that are designed for QoS, energy conservation, fault tolerance, and security strengthen are reviewed in details later in Section 4.5.

Classification based on routes disjointness type:

In the first two phases of multipath routing RDP and RMP, a multipath routing protocol may use one of three route restrictions when looking for routes; node-disjoint, link-disjoint, or non-disjoint routes. In node-disjoint routes, no nodes or links are shared by a route. In link-disjoint routes, one or more nodes can be shared by a route, however no links are shared. In non-disjoint routes, both nodes and links can be shared [11][17][103]. A multipath routing protocol should be one or mixed of the following types:

- **Node-disjoint multipath routing protocols:** such as approaches proposed in [18], [89], [92], and [104].

- **Link-disjoint multipath routing protocols:** such as the approach proposed in [17], TRAODV, and ORMAD.

- **Non-disjoint multipath routing protocols:** such as approaches proposed in [13], [65], [105].

2.9.4 Design issues of multipath protocols in MANETs

This section focuses on the most significant design issues of multipath routing in MANETs; QoS, fault tolerance, energy conservation, and security.

Multipath routing and QoS:

QoS is one of the most issues in MANETs that can benefit from multipath routing. The notion of QoS is mentioned earlier in this chapter, which is the performance level of services offered by a service provider or a network to the user in terms of many performance metrics of QoS such as the average end-to-end delay, packet delivery, and available bandwidth. The cost of transport and total network throughput may be included as parameters. The task of any QoS protocol is related to resource operations such as resource identification, resource request, resource reservation, and resource releasing, while the task of any QoS-aware routing protocol is to find a suitable route between the source and the destination, so that the route should have the necessary resources available to meet the constraints of QoS for the desired service. Both tasks together can be indicated by QoS routing [33].

The major challenge of providing multimedia services in MANETs is that some QoS metrics [106] such as packet delivery ratio, delay, and jitter must be satisfied. In MANETs, two characteristics impose two major challenges for provisioning QoS, the shared wireless medium and the mobility of nodes. Unlike wired networks in which most of the QoS solutions rely on the availability of precise link utilisation information, all traffic within the transmission range of a mobile node in MANETs contends for medium access. Therefore, medium access must consider the relevant service level of a flow and the impact of the flow on the neighbouring flows, which dramatically increase the complexity of medium contention.

In addition to affecting the dynamic change of load traffic, the node movement also affects on the primary routing path leading to a link break and as a result some packets may be lost. In a large scale network, this effect becomes more significant, especially with long communication paths. When a link is broken, a new RDP should be initiated, which leads to higher routing overhead and packet transmission delay. Therefore, reducing routing overhead and the number of routing control packets are significant to offer effective provisioning of QoS in MANETs.

AODV Backup Routing (AODV-BR) [105] tries to solve the delay problem while rediscovering a new routing path by intermediate backup nodes. Those backup nodes are arranged when route discovery phase and would forward packets automatically if they detect the original radio link is failure. However, the multimedia applications in MANETs are restricted by the unreliable radio link and insufficient bandwidth. Thus, backup nodes/paths protocols can forward packet temporarily but cannot increase the total throughput if the original routing path have no sufficient bandwidth.

A scheme is proposed in [90] where a packet is fragmented into small blocks which are distributed among available multiple routes. Then, some overhead is added to each packet with a lower failure probability. Network traffic is dispatched over multiple disjoined paths to minimise the packet drop ratio and improve the end-to-end delay.

An interfering-aware QoS multipath routing protocol is proposed in [107] for QoS-constraint multimedia and real-time applications in MANETs. A scheme is applied to evaluate available bandwidth according to the network capacities with different MAC protocols. It is concluded that maintaining multiple routes with stable bandwidth in MANETs leads to resource consuming. It is also concluded that a MAC protocol with power control scheme will decrease the interfering ratio between routing paths.

Video transport over MANETs with path diversity is studied in [87]. This approach mainly focuses on how to distribute the video traffic among multiple routes.

In this approach, multiple description coding is used to distribute video traffic over multiple paths. In Serial Multiple Disjoint Trees Multicast Routing protocol (Serial MDTMR) [108], the problem of real-time video communication over MANETs is addressed for both the unicast and multicast cases. For the unicast case, a multipath source routing protocol is applied to both interactive and video on-demand applications. For the multicast case, multiple tree multicast streaming is applied as a way to provide robustness for video multicast applications using a distributed double disjoint tree multicast routing protocol. However, this approach does not provide any suggestions to reduce the routing overhead while maintaining the ability to find disjoint routes.

A QoS-aware multipath DSR-based routing approach is proposed in [109]. This approach tries to help improving the reliability of the connections while balancing the load over multiple routes, which leads to decrease the end-to-end delay. A QoS-aware architecture is also proposed using a cross-layer scheme in which a network layer scheduler manages different priority traffics and operates according to the IEEE 802.11e MAC layer. One drawback of this approach is that it provides non-disjoint paths so that it is difficult to distinguish which of the paths are better than the others in terms of node and link status.

A recent approach based on the DSR protocol is proposed in [110]. This approach applies a cross-layer QoS-provisioning algorithm that uses information collected at different layers of the network's protocol stack. It develops a multipath routing scheme based on DSR protocol to provide multiple source-to-destination loop-free paths. Multipath design is analyzed with focusing on the benefits of load balancing and the video frame losses. A more recent approach called Distributed Cross-Layer QoS (DCLQ) architecture is proposed in [104] based on node-disjoint multipath routing to provide QoS guarantees for real-time traffic and best-effort traffic in MANETs. DCLQ implements per-hop QoS-aware priority scheduling and QoS consideration of MAC layer to ensure the flow of real-time with minimum routing control overhead while matching the requirements of the service level.

One of the most recent approaches of QoS-aware multipath routing is proposed in [111]. In this approach, an algorithm is proposed to optimise the source rate and the routing scheme for video streaming over MANETs. The algorithm uses dual decomposition to split the problem into multiple subproblems, and then solve each subproblem in at the same time. The fully distributed nature of the proposed algorithm leads to make the optimal results converge quickly. This characteristic leads to fast rerouting when the network topology changes due to node movement or channel failure. The approach also shares the computation among all the nodes, which leads to save the energy consumption of each node.

Multipath routing and fault tolerance:

MANETs are prone to numerous types of faults due to the mobility and dynamic topology, some of the most possible faults in a MANET [11] are summarised as follows:

- Transmission errors
- Node failures
- Link failures
- Route breakages (e.g. stale routes)
- Congested nodes or links

To be effective, a routing protocol in MANETs must deal with these types of faults. As mentioned earlier, multipath routing can be used to support reliability (fault tolerance) for both routing and QoS issues in MANETs. Node-disjoint and link-disjoint multipath routing can provide higher fault tolerance than non-disjoint multipath routing in MANETs.

A multipath extension to DSR that employs packet salvaging is proposed in [91]. Multipath routing is utilised in this approach for fault tolerance. If a source cannot send a packet due to a route failure, the packet can be routed using an alternative valid route.

Node-Disjoint Multipath Routing (NDMR) protocol is proposed in [92] as a modification and extension to AODV in order to include the path accumulation feature of DSR in RREQ and RREP packets, so that lower route overhead is used to discover multiple node-disjoint routing paths. NDMR reduces routing overhead dramatically and produces multiple node-disjoint routing paths.

MP-DSR is a multipath QoS-aware extension to DSR proposed in [93]. This protocol attempts to provide end-to-end reliability as the QoS metric.

A novel and nearly linear heuristic approach is proposed in [112] for constructing a highly reliable path set in MANETs environment.

AODV Multipath (AODVM) [89] is an extension to AODV, which introduces a framework for reliable routing in MANETs. It produces multiple routes with only node-disjoint property, which leads to more reliability in the set of routes.

A more recent framework is introduced in [94] which has investigated three aspects in modelling multipath routing in ad hoc networks; load balancing, delay, and reliability. Using these analytical results, given link broken probability, node processing rate, and traffic intensity, the reliability of a routing framework and the optimal traffic distribution pattern are estimated in this approach.

Multipath routing and energy conservation:

Energy conservation is crucial issue for maintaining the life-time of routes. One of the most significant reasons of a link failure is related to the batteries discharging of the nodes. Thus, both a single path and multipath routing protocol should be an energy-aware to be an energy-efficient protocol. This is the reason that many ad hoc routing protocols are proposed for the purpose of energy conservation. However, most of them rely on single path routing for data transmission sessions.

Unlike single path, multipath routing can improve the average time of a node failure and balance the load, so that it outperforms single path routing in such issues.

An energy-aware multipath routing protocol in MANETs called Multipath Power Sensitive Routing Protocol (MPSR) is introduced in [113]. MPSR shows how an efficient heuristic-based multipath scheme can improve the mean time to node failure and maintain the variance in the power of all the nodes as less as possible. MPSR is a flat topology in which every node is treated equally taking into account the critical concern of stability and end-to-end delay reduction.

Another multipath energy-efficient routing protocol for MANETs called Multipath Energy-Efficient Routing (MEER) is conducted in [114]. This approach utilises the advantages of on-demand protocols to prolong the network lifetime by using a rational power control mechanism.

The two approaches proposed in [113] and [114] are non-disjoint routing approaches, thus do not utilise the benefits of route disjointness, which is useful to balance the energy consumption among different nodes in disjoint routes.

An Ant-based Energy Aware Disjoint Multipath Routing Algorithm (AEADMRA) in MANETs is proposed in [115]. The proposed routing algorithm is based on swarm intelligence, especially on the ant colony based meta heuristic. Ant colony algorithms are a subset of swarm intelligence which consider the ability of simple ants to solve complex problems by cooperation. AEADMRA exploits the concept of a routing protocol called GRID [116] (the idea behind the name GRID is that the geographic area is treated as a number of logical grids) to discover multiple energy aware routing paths with a low routing overhead.

A good combination between QoS and energy conservation issues is introduced in [18], in which a minimum Energy Collision-Constrained node-disjoint multipath routing Algorithm (ECCA) is proposed for MANETs. ECCA defines correlation factor to weigh the collision probability among node-disjoint multipath, and then calculates an upper limit for correlation factor according to service requirement and finds a minimum energy node-disjoint multipath routing to satisfy that upper limit. The main advantage of this approach is that it deals with the collision problem in node-disjoint multipath taking into account the energy conservation issue. It tries to find a trade-off between minimum energy and collision avoidance when transmitting data simultaneously.

A more recent approach is conducted in [117], which proposes a simple scheme for multipath routing based on spatial relationships among nodes, and then combines stochastic geometric and queuing models. The proposed approach develops a continuum model for MANETs by carrying out an evaluation of different types of scenarios. It proposes a family of energy balancing strategies and studies the spatial distributions of energy loads based on some statistics. It shows how the optimisation depends on the relative values of energy storage, supply rates, and network load characteristics.

Multipath routing and security:

The cooperative nature of MANETs leads to increase the vulnerability of MANETs. Threats and attacks can intrude a MANET in a distributed environment, especially in absence of any kind of centralised administration. Multipath routing can offer many benefits for securing routing protocols in MANETs.

A reliable (secure) multipath routing approach is proposed in [118] for MANETs. In this approach, multiple routes are selected so that security can be guaranteed against some malicious nodes using coding technique. The approach introduces an analytical study for both proactive and reactive routing protocols in MANETs.

Scheme proposed in [119] tries to handle the security issue by presenting trust and key management models for intrusion detection and prevention. The existence of multiple routes between nodes in MANETs is exploited to increase the robustness of transmitted data confidentiality. The proposed algorithm is tested against time for intrusion detection and robustness.

Another multipath routing algorithm for data security enhancement, which is called Multipath TCP Security (MTS), is conducted in [120]. In MTS, the source node chooses multiple routes adaptively rather than testing the stored routes one by one. Simulation results show that this approach provides a good level of security and performance. Compared to AODV and DSR, MTS has a better number of participating nodes and highest interception ratio. Results also show that at high mobility, MTS performs better in respect to the other two routing protocols in terms of average end-to-end delay.

More recent approach is introduced in [121] to secure data transmission in MANETs using multipath routing. This approach presents and evaluates a scheme, in which multipath routing is combined with feedback mechanism to handle misbehaviours on data delivery comes by one or more misbehaving nodes in a MANET. Data and control packets are transmitted through two node-disjoint paths. The source is notified of suspected behaviour of any intermediate node using a feedback mechanism.

Secure, Disjoint, Multipath Source Routing Protocol (SDMSR) [122] is another recent multipath approach. This approach concerns the problem of secure routing in fully distributed MANETs using multipath routing. SDMSR starts with studying the effect of multipath routing in terms of security, and then it proposes a multipath heuristic algorithm to protect the route discovery and secure the routing protocol while reducing security overhead.

2.10 Summary

An overview of MANETs covering the characteristics, applications, challenges, and a reference model of MANETs are presented in this chapter. The most significant issues in MANETs such as routing, QoS, security, and multicasting are reviewed and the routing issue is more focused in Section 2.8 because it is the general scope of this research. Routin aspects covered in this section are characteristics, issues, requirements, and classification of routing protocols in MANETs including proactive, reactive, and hybrid protocols. A review of state-of-the-art multipath routing is presented in Section 2.9 covering applications, classification, and design issues of multipath routing in MANETs. A novel aspect of this review is that multipath routing protocols in MANETs are classified into new four paradigms. This classification is figured out based on analyzing the most significant aspects and properties of multipath routing in MANETs. The features and the differences between node-disjoint, link-disjoint, and non-disjoint multipath protocols are discussed also in this review. In the next chapter, an experimental study is presented to evaluate the performances of reactive routing protocols in MANETs. The evaluation is conducted for three reactive routing protocols, namely AODV, DSR, and TORA against each other, and then for the two traditional multipath protocols DSR and TORA against two multipath extensions to AODV, namely AOMDV and MRAODV.

Chapter 3

Experimental Study of Reactive Multipath Routing Protocols

3.1 Introduction

As mentioned earlier in the previous chapter, routing is one of the most challenging issues and interesting research areas in MANETs. A routing protocol is developed mainly to detect and maintain the optimal route to send data packets between a source and destination nodes. In traditional routing protocols, each node in the network maintains a routing table which lists the next node to each destination that is desired to be communicated with the source node. A routing protocol of MANET should be able to handle a very large number of autonomous nodes with limited resources such as bandwidth and energy.

Many ad hoc routing protocols have been proposed so far and each protocol is developed with some advantage over the other protocols. The performance of each protocol is different from the others depending on the structure, features, and the applications of the protocol. For this reason, some ad hoc routing protocols are obsolete while the others are still working and extended to more recent versions.

An experimental study is presented in this chapter which focuses on comparing the performance of reactive routing protocols in MANETs. The evaluation is conducted between three reactive routing protocols, namely DSR, AODV, and TORA, and then between two traditional multipath protocols, namely DSR and TORA and two multipath extensions to AODV, namely AOMDV and MRAODV. Finally, a results study of the simulation that is performed using NS2 (version 2.26 on Linux platform - Fedora 5) is presented. The reason that NS-2.26 is used for the simulations of this experimental study is that NS2.26 incorporates stable and well-tested implementations of DSR, AODV, TORA, and AOMDV routing protocols [56]. MRAODV routing protocol is implemented in NS2 by modifying the existing implementation of AOMDV protocol.

Routing protocols in MANETs have been tested and evaluated in so many literatures, especially in relation to the comparison of their performance from several perspectives.

Numerous comparison studies are carried out to evaluate the most common reactive protocols in MANETs, AODV and DSR such as studies presented in [64], [66], and [68]. Simulation results of these studies have shown that DSR is better than AODV in general. However, when the network size increases, AODV becomes better because DSR is a source routing protocol. Results also have shown that the source routing protocols such as DSR had very high throughputs while the distance vector protocols such as AODV exhibit a very short end-to-end delay of data packets.

These studies have focused more on reactive flat protocols. As concluded by these studies, a combination between AODV and DSR could be a solution with better performance than the original AODV and DSR. The idea of combining AODV and DSR features is exploited and a new multipath extension to AODV called Dynamic Manet On-demand (DYMO) routing [65] is produced recently. As for DSR, DYMO enables the source node only to record one possible next hop to every destination while in the original AODV, every node records the next hop to send a packet to a specific destination.

In [67], a comparison study is introduced for four typical ad hoc routing protocols, namely DSDV, TORA, DSR, and AODV. This study is carried out in more dynamic environment. This means that it takes the mobility parameter into consideration. However, this study does not concern the aspects of single path and multipath routing which makes a clear difference in the routing performance, especially in overall throughput.

A recent study is performed in [69] with performance evaluation and comparison of four typical routing protocols of MANETs which are discussed from the perspective of varying network size. These protocols are DSDV, DSR, AODV, and, TORA. In this study, jitter and connectivity are used as computer metrics.

A more recent study is carried out in [70] to compare DSR and AODV along with the traditional proactive protocol DSDV. The experimental is performed by varying network load, mobility, and network size. This comparison is performed in the context of comparing the single path protocols against each other and later on, the paper compares some multipath protocols against each other taking into account the QoS parameters. However, the paper is not coherent and the objectives of the paper are not clear because the paper does not compare between single path and multipath protocols. In this paper, it is not clear why both comparisons are performed in the same context. Additionally, the paper considers DSR as a single path protocol which is not absolutely true. DSR is well-known as a multipath traditional protocol in MANETs.

The experimental study introduced in this thesis presents a performance evaluation using a simulation study for three traditional reactive protocols in MANETs, namely DSR, AODV, and TORA. This evaluation is performed for the three traditional protocols against each other and then, for the traditional single path against traditional multipath protocols, and finally for two multipath extensions to AODV against traditional multipath protocols. The first advantage of this study is that TORA, a multipath and reactive protocol, is involved in the evaluation. Involving TORA in the studies of this thesis is justified in the experimental evaluation of multipath protocols presented later in this chapter. The second advantage of this experimental study is that the evaluation involves two multipath extensions to AODV; the first one is AOMDV which is developed early in the year 2001 and the second is MRAODV which is more recent (developed in 2004). The third advantage of this study is that the evaluation is performed in terms of four performance metrics; packet delivery fraction, average end-to-end delay, routing packets overhead, and throughput. Mobility is used as a main input parameter in the simulation process of this experimental study. The goals of the experimental study presented in this chapter are to narrow down the research area of this thesis, recognise the lack in the existing protocols, and consequently to determine the starting point of our research.

3.2 The Simulation Process of Reactive Protocols Evaluation

This section presents the simulation process of the experimental evaluation performed on three traditional reactive routing protocols in MANETs, namely DSR, AODV, and TORA which are discussed in Chapter 2. The same environment is used for the simulations of all protocols using NS2. This section describes the mobility and traffic scenarios, input parameters, and performance metrics used in the simulation process. The results of the study and evaluation are presented later in the next section.

3.2.1 Simulation environment

NS2 is a discrete event network simulator for network research and it is running on UNIX-like operating systems [71]. The simulator consists of two parts; an object oriented simulator part in C++ and an Object Tool command Language (OTcl) part to execute command scripts of the user. The C++ part is used for fast execution and therefore useful for running protocols, while the OTcl part is used to configure the input via user scripts and it has the advantage that the entire system has not to be recompiled when an input has changed.

A very important note which is worthy to be mentioned here is that the environment of the simulations of NS2 used in this thesis including network size (number of nodes), simulation time, speeds, packet sizes, queuing, traffics, MAC layer specifications, mobility and connection scenarios, and performance metrics are all inspired from the NS2 simulation environments that are commonly used with slight differences in so many literatures to evaluate routing protocols in MANETs (e.g. [13], [17], [105], and [124]). Environment of all simulations in this thesis is illustrated in Chapter 7 (the results study chapter of this thesis) by the configuration of fixed parameters and different scenarios of the simulations which are ilustrated by Tables 7.1 and 7.2 respectively.

Simulation scenarios including fixed parameters, traffic models, and mobility models are constructed prior to carrying out the NS2. Traffic connections of Transmission Control Protocol (TCP) or Constant Bit Rate (CBR) can be set up between mobile nodes using a generator script traffic scenario. This traffic generator script is available under the directory *ns/indep-utils/cmu-scen-gen* in NS2 installed package, and it is called *cbrgen.tcl*. It is used in this thesis to create CBR traffic connections for the simulations. Command (A.1) in Appendix A represents the traffic scenario generator script used to configure traffic models of the simulations using NS2 [72].

CBR traffic sources are used with a packet size of 512B and IEEE 802.11b wireless standard of speed 11Mbps which is used for MAC layer configurations. Finally, protocols maintain a send buffer of 64 packets which is fixed during the simulation process. For the simulations carried out, traffic models are generated for 20, 50, 80, and 100 nodes with maximum CBR traffic sources 10, 30, 50, and 60, and maximum number of connections of 15, 40, 70, and 90 links respectively for each number of nodes with a transmission rate of 10Kbps (usually uniformly chosen between 0 and 20Kbps [75]). The node movement generator used to configure the simulator is available under the directory *ns/indep-utils/cmu-scen-gen/setdest* in NS2 installed package which consists of setdest{.cc,.h} and makefile. Command (A.2) in Appendix A represents the node movement generator script used to configure the mobility models of the simulations using NS2 [73].

The mobility model used is the random waypoint model [76] in a rectangular area. The area used for the simulation is 500m x 500m with 50 nodes scattered randomly. Based on the random waypoint model, each node moves from a random location to a random destination with a speed chosen randomly so that the maximum speed of the nodes is set to 20m/s, a node pauses for a while and then moves again to another random location within the specified area.

For packet transmission, a packet starts travelling from a source chosen randomly with a speed of 10Kbps. Once the packet reaches the destination, another random destination is targeted after a pause. Simulations are run for 250 seconds and the pause time is varied as 0s, 10, 20, 40, 50, 100, and 250 seconds. All protocols are simulated using the same mobility and traffic scenarios for more accurate results. Simulation results are evaluated based on the average values for all scenarios of the simulation against the mobility (pause time).

Regarding buffering, packets are dropped if they wait in the node buffer for more than 30s. An interface queue is used to maintain packets (both data and routing) sent by the routing layer. When MAC layer is ready, it transmits these packets and then releases the interface queue. The maximum size of interface queue used for simulations is 50 packets using a priority queue. A higher priority is assigned for routing packets and a lower for data packets.

3.2.2 Input parameters

Mobility is considered here the most important input parameter that affects the behaviour of the routing protocols under study. Pause time is used to measure the degree of mobility so that a small pause time value indicates a high mobility (e.g. pause time = 0 means that nodes do not stop). On the other hand, a large pause time value indicates a low mobility (e.g. pause time = 250 sec means that nodes do not move). Medium mobility is considered here in this thesis at 40 and 50 seconds.

3.2.3 Performance metrics

The performance metrics used to evaluate the simulation results are summarised as follows:

- Packet Delivery Fraction (PDF): represents the ratio of the data packets delivered to the destination to the sent packets [77].
- Average end-to-end Delay (AVGD) of data packets: the average time a packet takes to reach its destination including delays caused by buffering, queuing, retransmission delay propagation time, and transfer time [78].
- Normalised routing load (Routing Packets Overhead - RPO): represents the number of routing packets transmitted per data packet delivered to the destination [77].
- Throughput: represents the number of packets successfully received by their final destination per unit time [78]. It is worthy to notice that there is a difference between PDF and throughput in this thesis based on the definitions mentioned above.

Steps of executing the simulation in NS2 are presented in details in Appendix A. Commands of the simulator, the form of output files, and figures of the visualisation are also presented in Appendix A.

3.3 Results Study of Reacive Protocls Evaluation

In this section, results study and evaluation of the simulations are presented to compare the three traditional reactive routing protocols, namely DSR, AODV, and TORA which are discussed earlier in Chapter 2. Evaluation is accomplished for all protocols under the same circumstances according to the performance metrics of the simulation environment which are defined in the previous section.

3.3.1 Packet delivery fraction

All protocols perform particularly well in terms of packet delivery fraction in all mobility scenarios. As shown by the simulation results of the average raw data of all scenarios of the simulations regarding PDF metric which are listed in Table 3.1

against mobility scenarios, and as illustrated by Figure 3.1 which represents the raw data of PDF, DSR has the highest average packet delivery fraction, and then TORA and AODV respectively.

Table 3.1: Packet delivery fraction (the average raw data of all scenarios of the simulations against mobility)

PDF			
Pause Time	**DSR**	**AODV**	**TORA**
0	97.66974	92.836235	97.421186
10	99.18448	90.59411	94.48411
20	91.58919	93.80405	96.44187
30	94.79524	77.38466	96.11287
40	92.8721	91.622905	90.46329
50	96.0638	92.761635	96.23079
100	98.97	94.33	95.63681
250	97.06942	94.98	96.91983

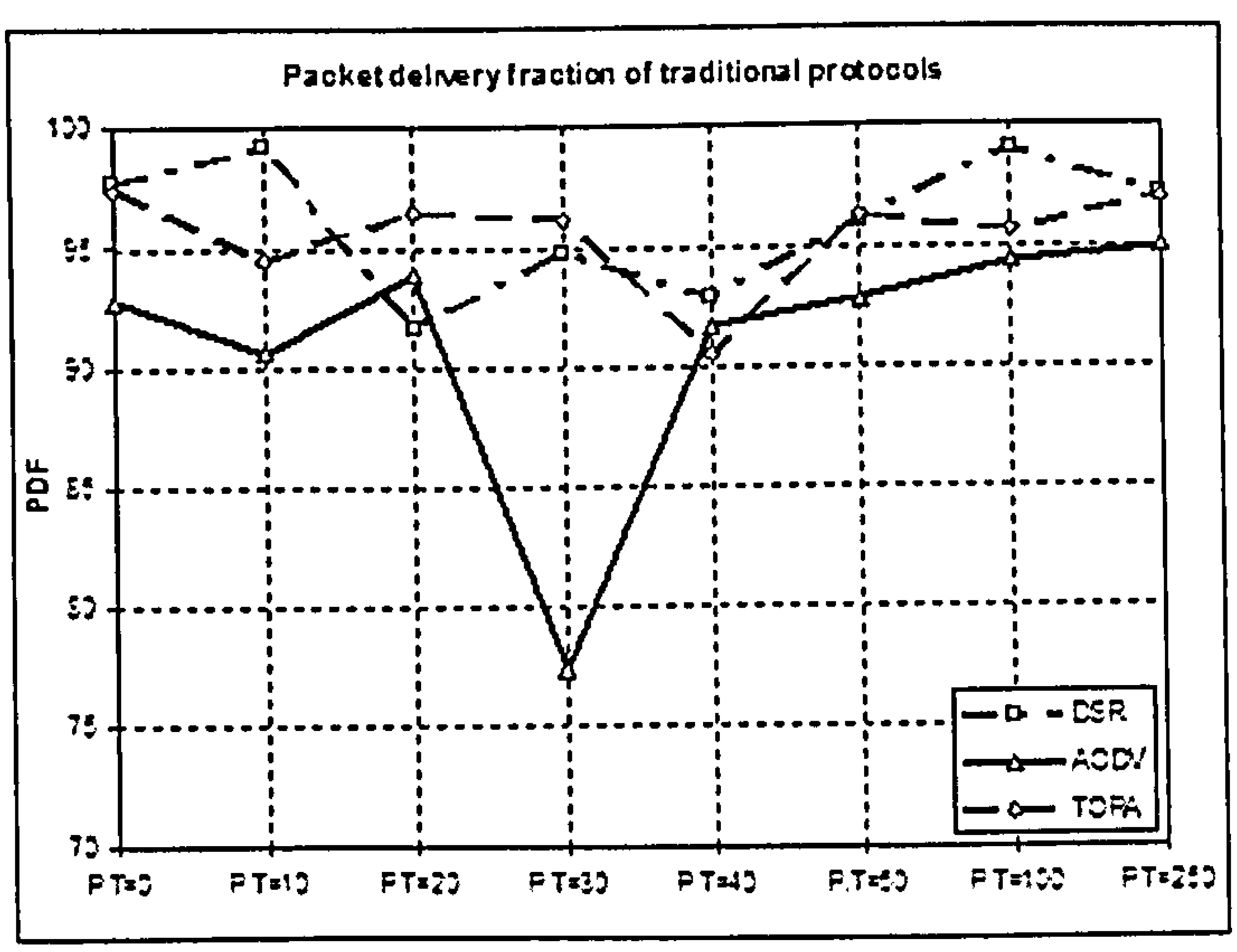

Figure 3.1: Comparison of packet delivery fraction

3.3.2 Average end-to-end delay

As shown by the simulation results of the average raw data of all scenarios of the simulations regarding AVGD metric which are listed in Table 3.2 against mobility scenarios, and as illustrated by Figure 3.2 which represents the raw data of AVGD, AODV protocol has the lowest average end-to-end delay compared to DSR and TORA , especially in high mobility scenarios. Even though AODV is a single path protocol, it outperforms both traditional multipath protocols DSR and TORA in terms of AVGD. By comparing DSR and TORA, DSR has a total average performance better than TORA in terms of AVGD.

Table 3.2: Average end-to-end delay (the average raw data of all scenarios of the simulations against mobility)

AVGD			
Pause Time	**DSR**	**AODV**	**TORA**
0	0.262538867	0.374687933	0.436345333
10	0.472643833	0.3554784	0.385811667
20	0.488896167	0.325468367	0.286315667
30	0.488623367	0.262696667	0.821743333
40	0.655471767	0.426948633	0.425048333
50	0.438954633	0.26756602	0.487226667
100	0.279350033	0.590044933	0.276636
250	0.4201685	0.608750477	0.413954667

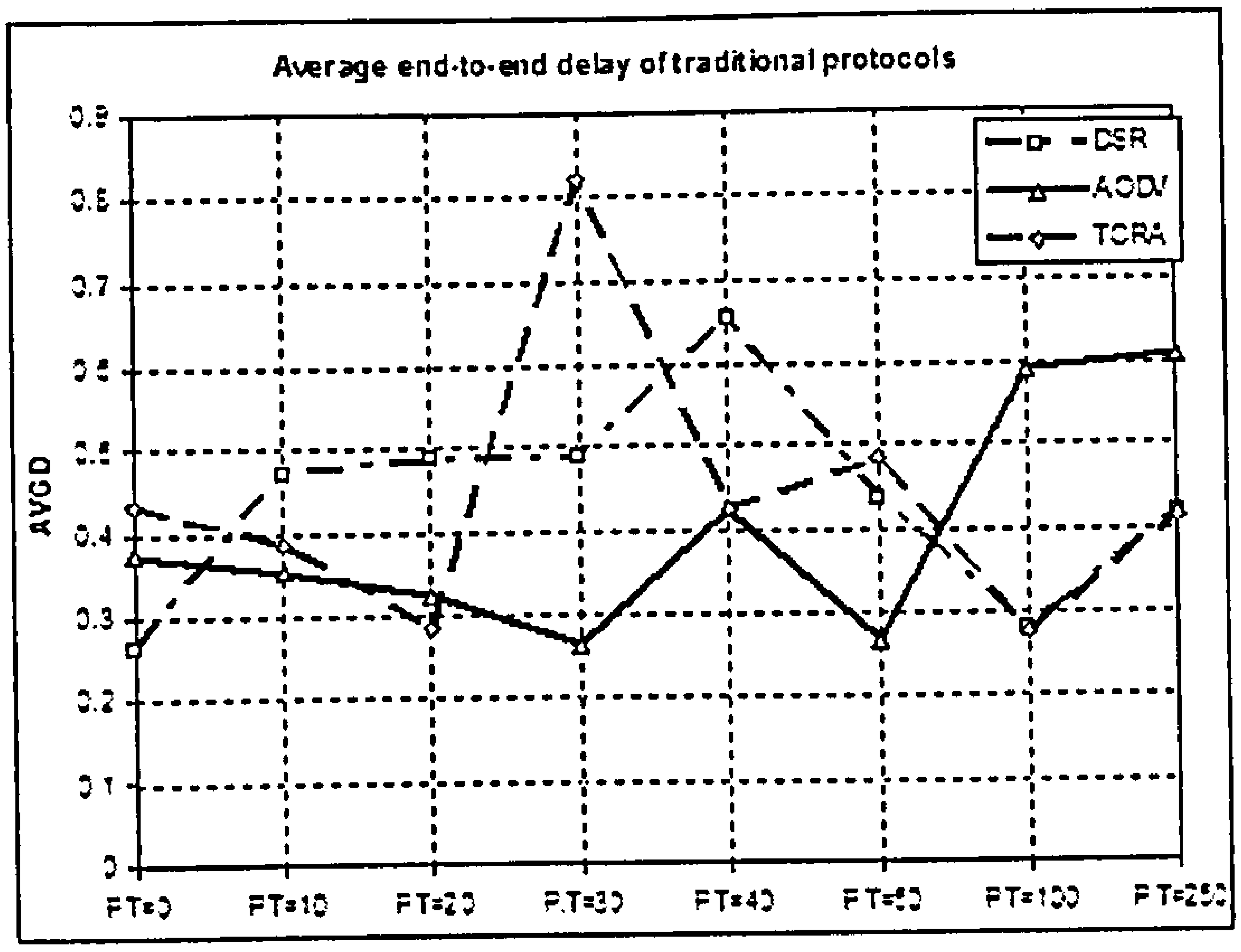

Figure 3.2: Average end-to-end delay for each protocol

3.3.3 Routing packets overhead

As shown by the simulation results of the average raw data of all scenarios of the simulations regarding RPO metric which are listed in Table 3.3 against all mobility scenarios, and as illustrated by Figure 3.3 which represents the raw data of RPO, TORA outperforms DSR and AODV in terms of the average routing packets overhead during all mobility scenarios. DSR performs significantly lower routing overhead than AODV which means that DSR has a better performance than AODV in terms of RPO.

Table 3.3: Routing packets overhead (the average raw data of all scenarios of the simulations against mobility)

RPO			
Pause Time	**DSR**	**AODV**	**TORA**
0	0.206	0.518	0.231
10	0.367	0.601	0.212
20	0.43	0.547	0.284
30	0.467	0.566	0.175
40	0.632	0.687	0.203
50	0.322	0.661	0.278
100	0.103	0.567	0.327
250	0.284	0.502	0.299

3.3.4 Throughput

As shown by the simulation results of the average raw data of all scenarios of the simulations regarding throughput metric which are listed in Table 3.4 against mobility scenarios, and as illustrated by Figure 3.4 which represents the raw data of throughput, DSR has the highest average throughput, and then TORA and AODV respectively.

As shown by the simulation results of the reactive protocols DSR, AODV, and TORA, DSR outperforms AODV and TORA in terms of data packet delivery and throughput, especially in high mobility scenarios while AODV outperforms DSR and TORA in terms of average end-to-end delay, especially in high mobility scenarios.

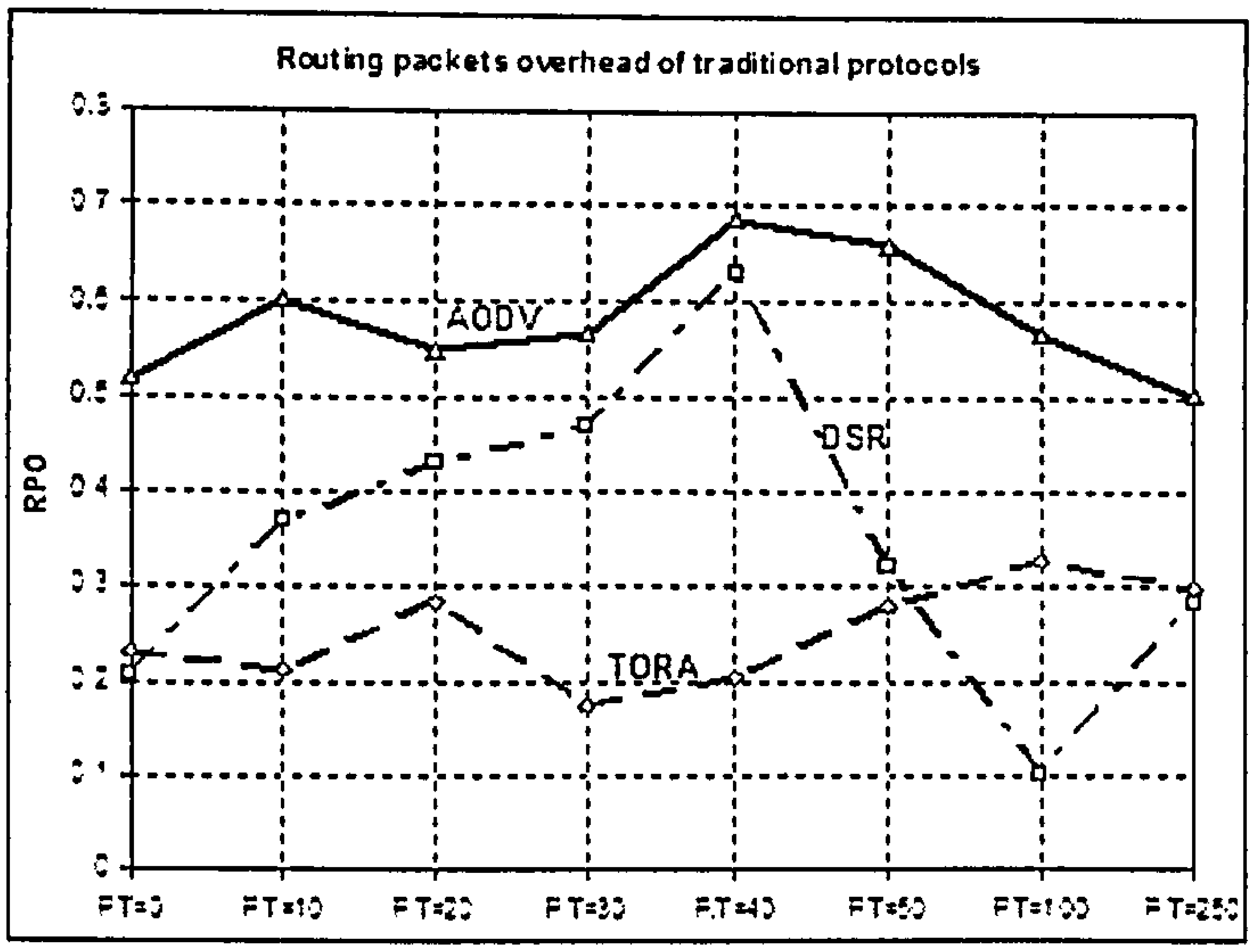

Figure 3.3: Routing packets overhead for each protocol

Table 3.4: Throughput (the average raw data of all scenarios of the simulations against mobility)

Throughput			
Pause Time	DSR	AODV	TORA
0	1105	1087	1113
10	1115	1081	1081
20	1073	1094	1106
30	1116	911	1099
40	1105	1111	1035
50	1109	907	1101
100	1117	1103	769
250	1103	1101	1108

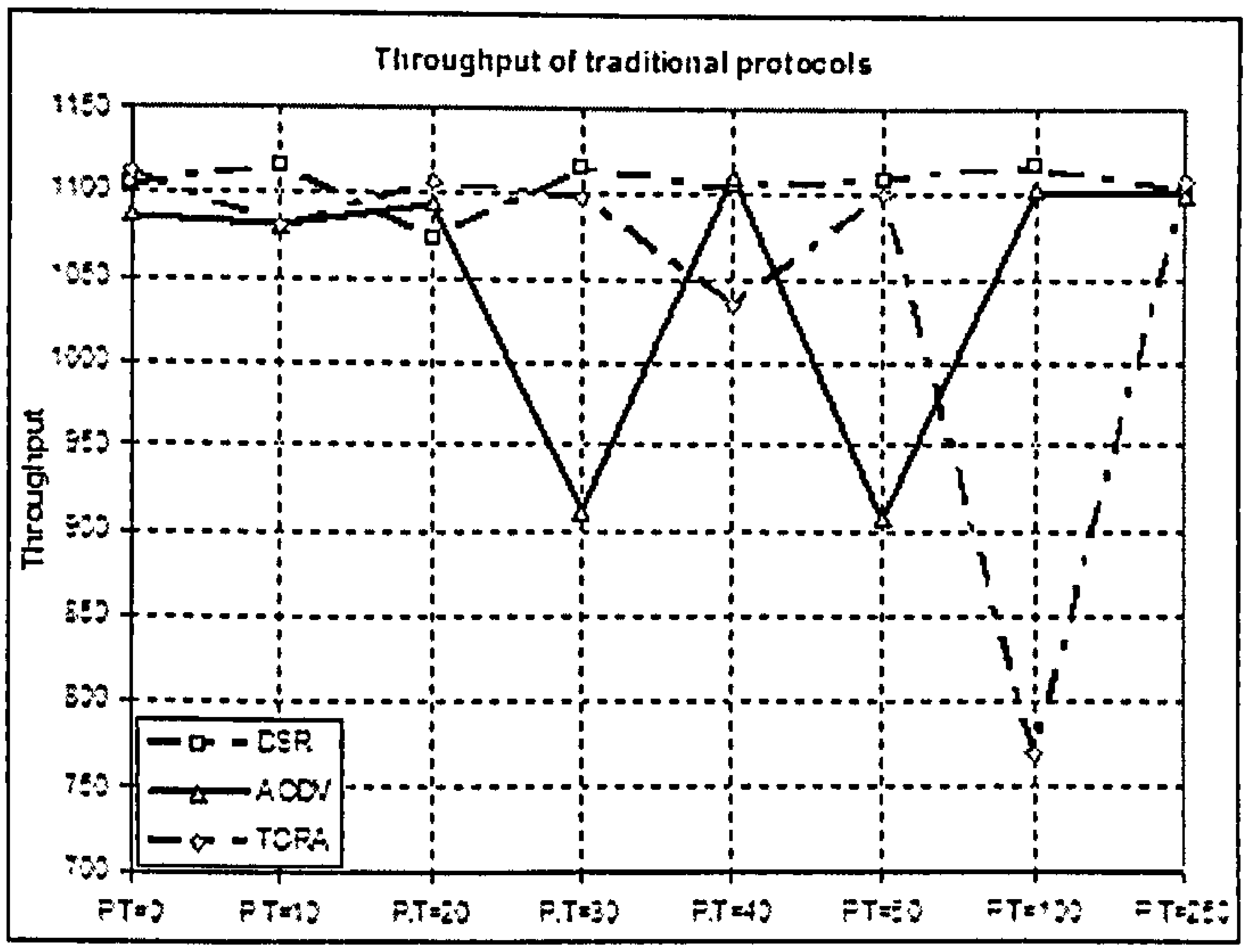

Figure 3.4: Throughput for each protocol

TORA outperforms DSR and AODV in terms of routing packets overhead in all scenarios of the mobility.

3.3.5 Evaluation of low and medium mobility scenarios

As shown in Table 3.1 and Figure 3.1, DSR still outperforms the other protocols in terms of PDF in medium and low and medium mobility scenarios, however AODV performance converges to DSR performance in low mobility. TORA performance also converges to DSR performance in both low and medium mobility. Regarding AVGD, DSR and TORA performances converge to AODV performance in low mobility. However, AODV is still better in high and medium mobility scenarios which is clear by Table 3.2 and Figure 3.2.

Regarding RPO, it is clear that TORA outperforms the other protocols in all mobility scenarios. However, as shown in Table 3.3 and Figure 3.3, DSR performance converges to TORA performance in low mobility scenarios.

Regarding throughput, it is shown by Table 3.4 and Figure 3.4 DSR is better in medium and low mobility in addition to high mobility scenarios.

3.4 Evaluation of traditional single path and multipath protocols

In this section, a simulation-based evaluation of traditional single path against traditional multipath routing protocols in MANETs is introduced for the same typical routing protocols analyzed in the previous sections. In this section, protocols are evaluated from the perspective of single path and multipath features. The evaluation is performed here for AODV which represents traditional single path protocols against DSR and TORA which represent traditional multipath protocols.

3.4.1 Packet delivery fraction

Figure 3.5 shows that the average of the two traditional multipath protocols outperform the traditional single path protocol in terms of the average PDF, especially in high mobility scenarios. However, the performance of traditional single path protocol converges to the performance of traditional multipath protocols in low mobility scenarios. This can be justified as the following; the system can still operate in multipath protocols even if one or a few of the multiple routes between a source and destination fail.

3.4.2 Average end-to-end delay

Figure 3.6 shows that traditional single path protocol outperforms the average of the two traditional multipath protocols in terms of the average AVGD, especially in low mobility scenarios. However, the performances converge to each other in low and high mobility scenarios in which the two multipath protocols slightly perform better than the single path protocol. This can be justified as the following; because of the reactive feature and the effective mechanism of route discovery process in AODV, it has a good performance in terms of AVGD which is very close to the performance of multipath protocols, and individually it is better than each one of

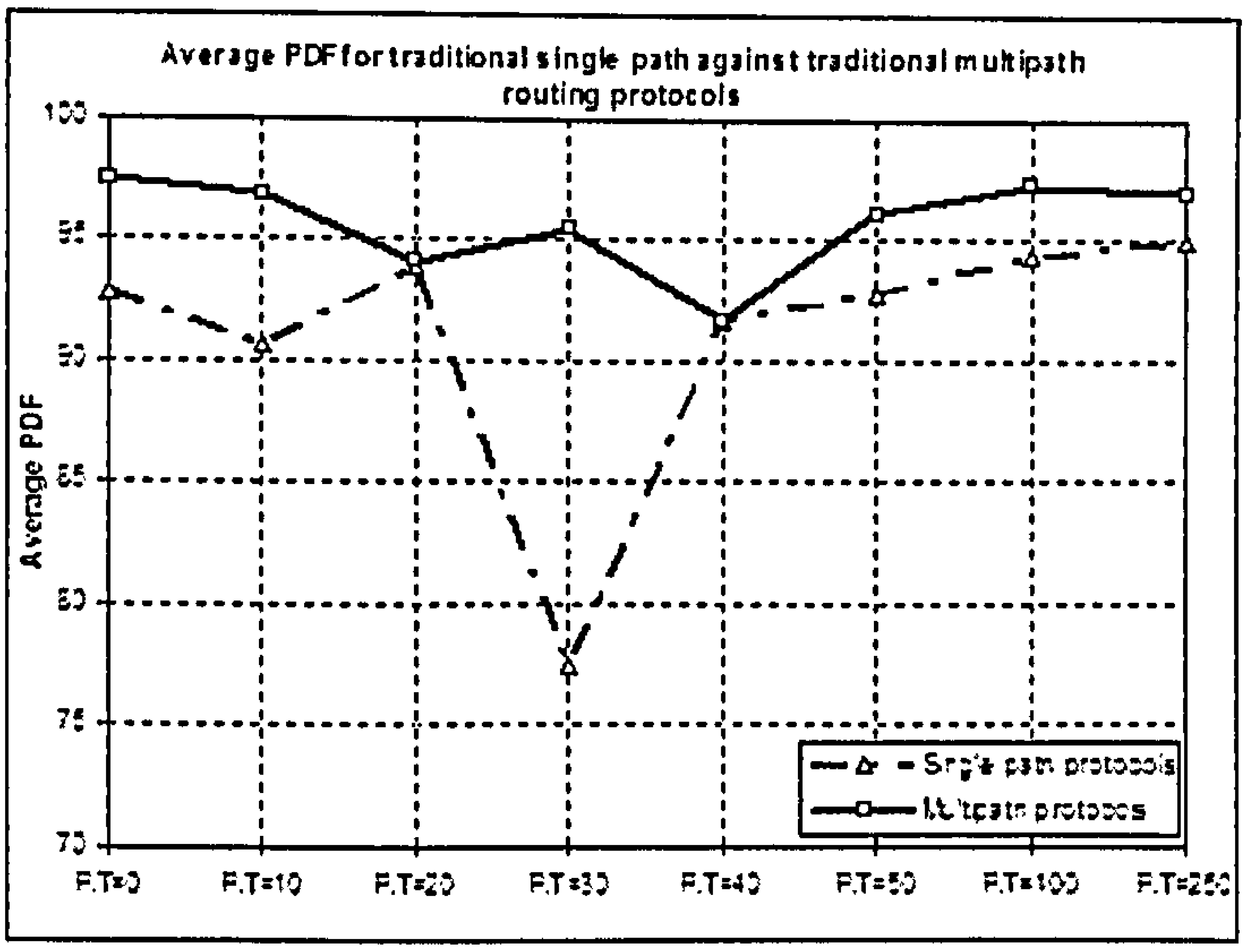

Figure 3.5: Average PDF of single path against traditional multipath routing protocols

the traditional multipath protocols DSR and TORA in terms of AVGD, especially in high and medium mobility scenarios.

3.4.3 Routing packets overhead

Figure 3.7 shows that the average of traditional multipath protocols outperforms the traditional single path protocol in terms of the average RPO, especially in high and low mobility scenarios. However, the performance of the single path protocol is better in medium mobility scenarios. Even though TORA individually has the best performance of RPO in all mobility scenarios, the average of total performance of both multipath protocols is affected by the bad performance of DSR in terms of RPO, especially in medium mobility.

3.4.4 Throughput

Figure 3.8 shows that the average of traditional multipath protocols outperforms the traditional single path protocol in terms of the average throughput, especially in

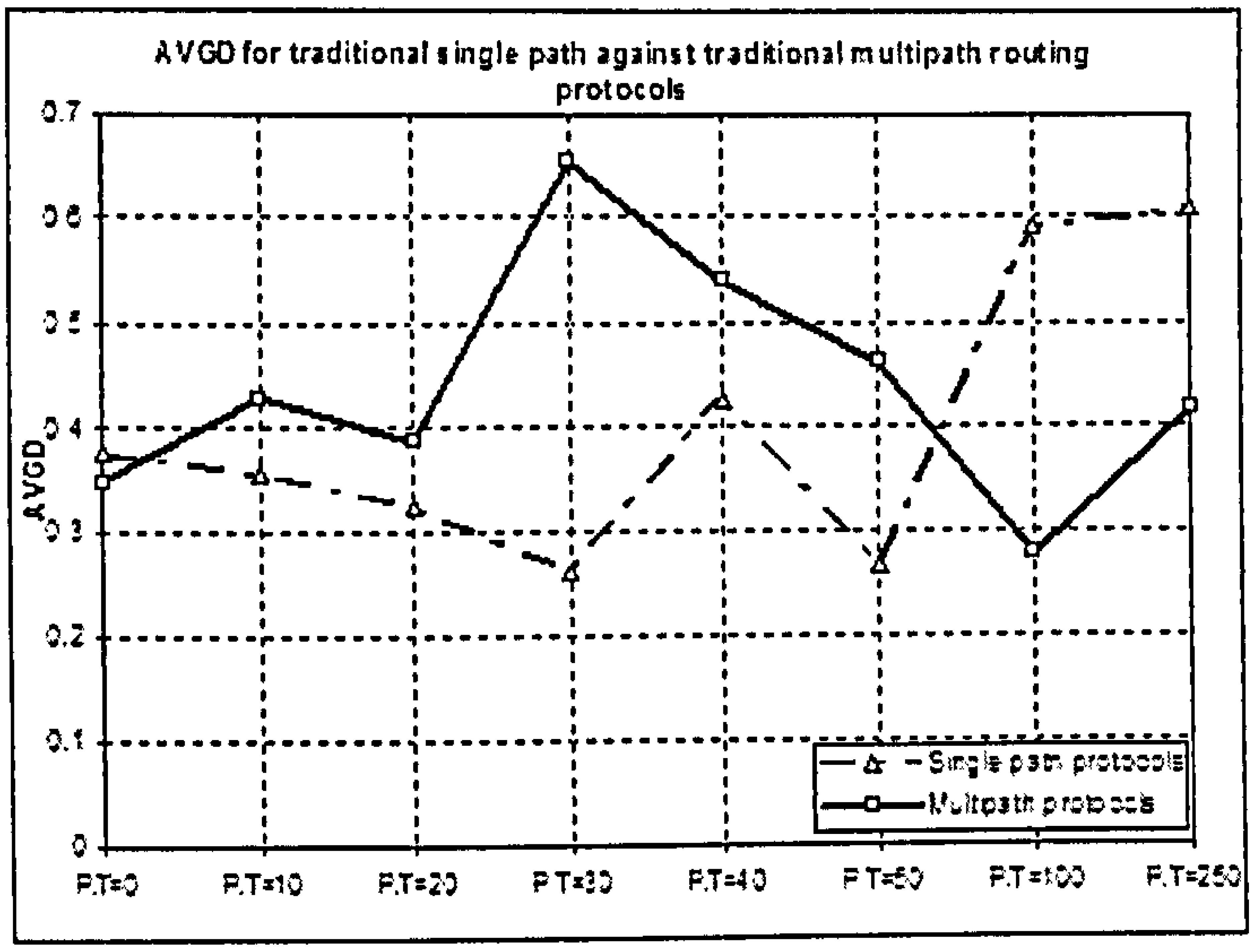

Figure 3.6: Average AVGD of single path against traditional multipath routing protocols

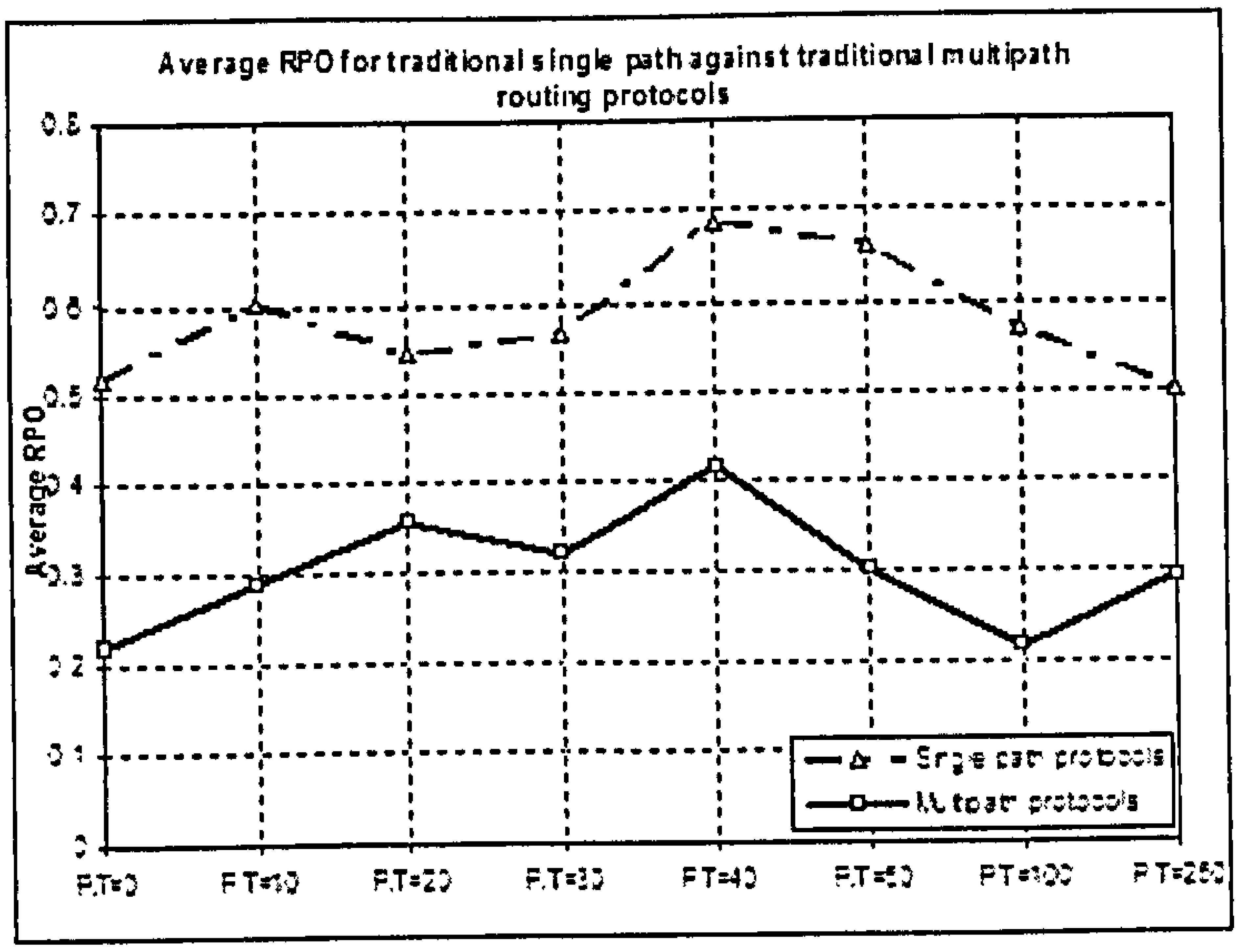

Figure 3.7: Average RPO of single path against traditional multipath routing protocols

high and medium mobility scenarios. However, the performance of the single path protocol is enhanced in low mobility scenarios.

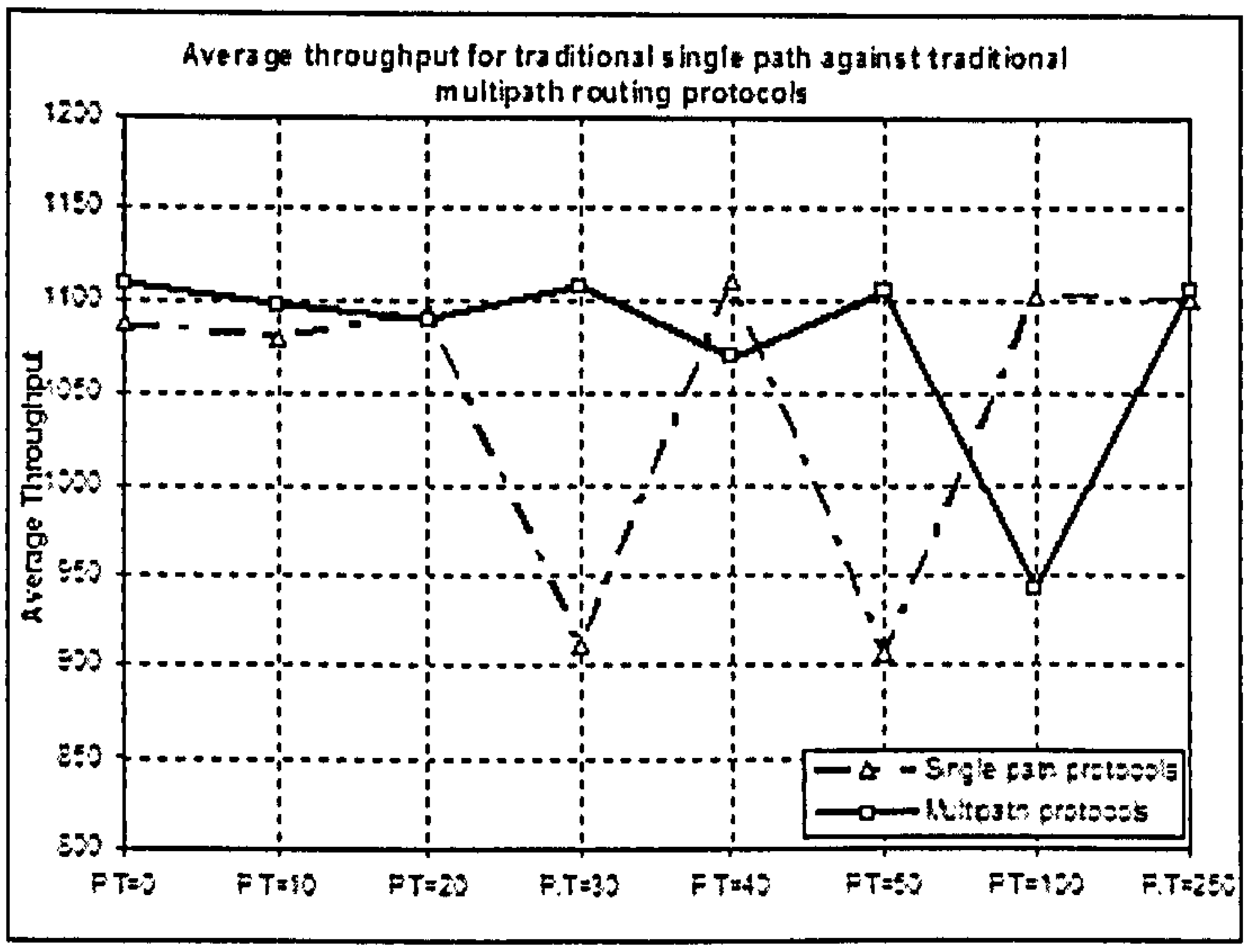

Figure 3.8: Average throughput of single path against traditional multipath routing protocols

Figure 3.9 shows a comparison of the average performance ratio of traditional multipath to traditional single path routing protocols in terms of each performance metric individually.

3.4.5 Discussion

Based on the results of the experimental evaluation presented in this section for the most common traditional routing protocols in MANETs, the main point of the research scope is determined by verifying whether it is feasible to develop AODV protocol to new multipath extensions as it is well-known and well-proven ad hoc routing protocol, or there is any other protocol that is a more feasible candidate.

Figures 3.10, 3.11, 3.12, and 3.13 show the average performance for each protocol in terms of PDF, AVGD, RPO, and throughput respectively. It is shown that DSR

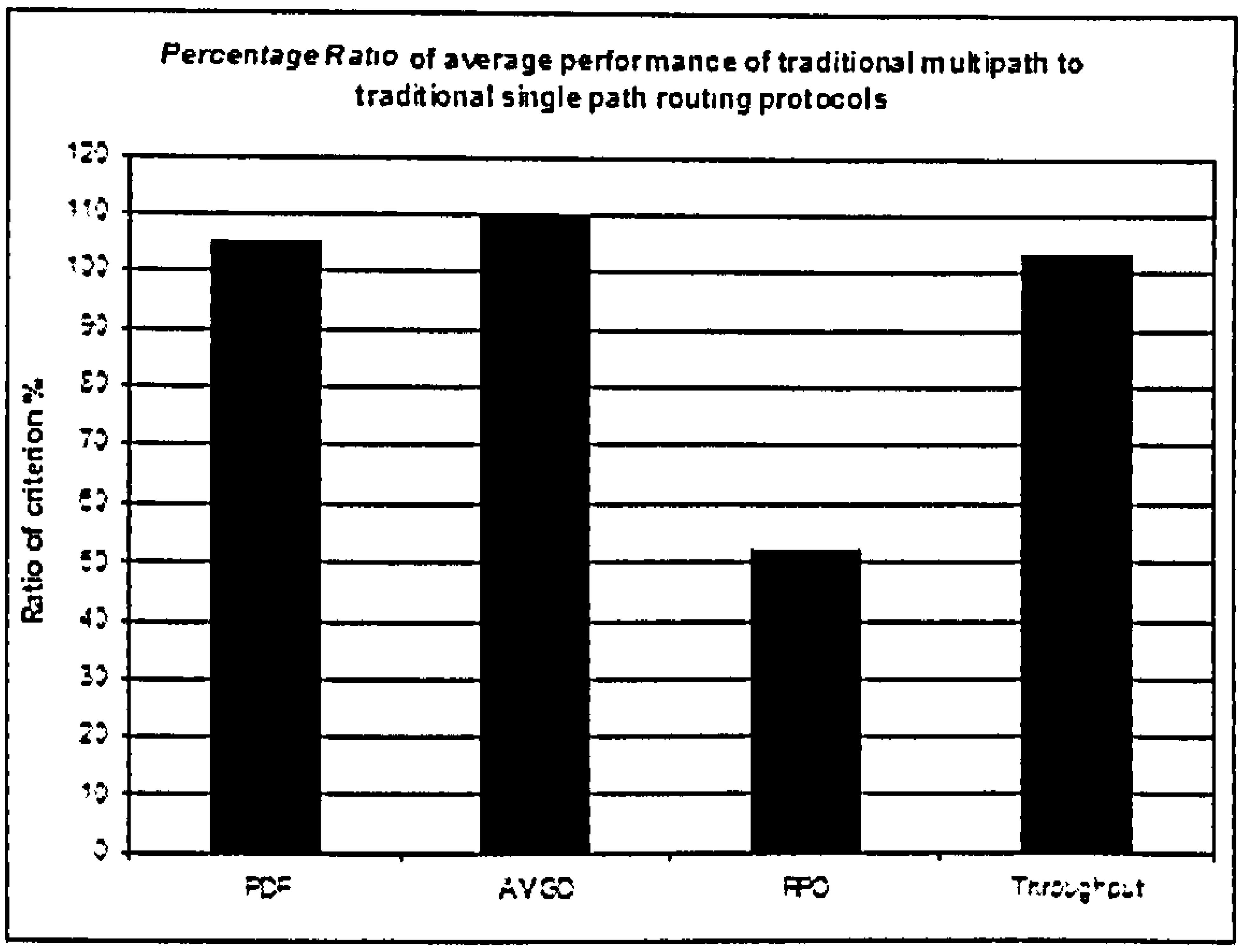

Figure 3.9: Percentage of the average performance of traditional multipath protocols with respect to the single path protocol

and TORA (traditional multipath) outperform AODV (traditional single path) in all performance metrics except in AVGD by which AODV outperforms DSR and TORA. However, it should be noticed that AODV performance is very close to traditional multipath protocols performance in terms of PDF, RPO, and throughput even with its single path feature.

Generally, simulation results show that traditional multipath protocols outperform the single path protocol in terms of all performance metrics except AVGD. The results study shows that the rate of routing packet overhead is less in a network that uses multipath routing. It also shows that using multipath routing protocols results in a higher throughput and packet delivery fraction than that in single path protocols. Single path protocol performs well only in terms of the average end-to-end delay which is reduced in single path routing.

Even though multipath protocols have generally better performance than the single path protocol, AODV has individually a good performance in terms of AVGD

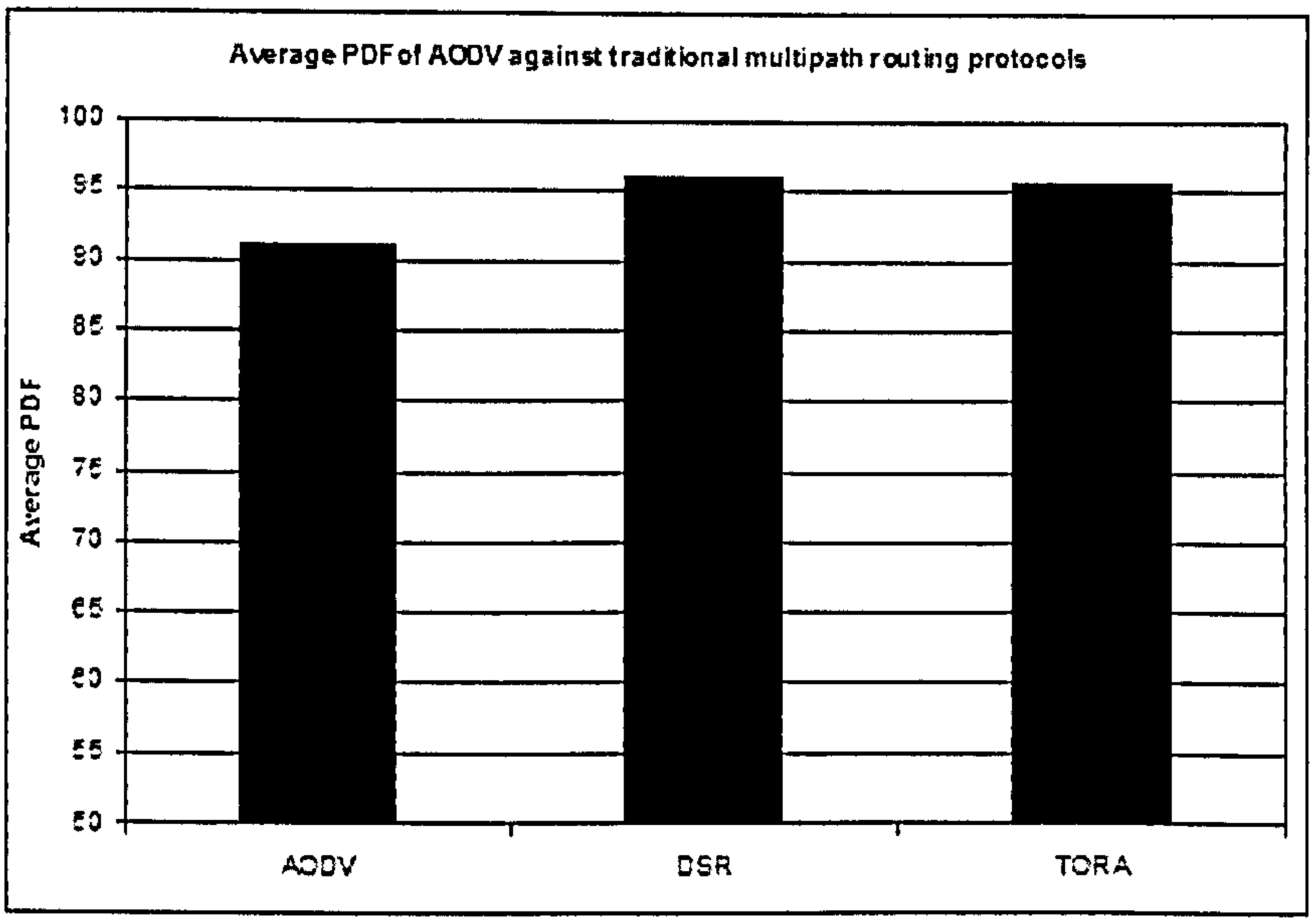

Figure 3.10: Average performance of each protocol in terms of PDF

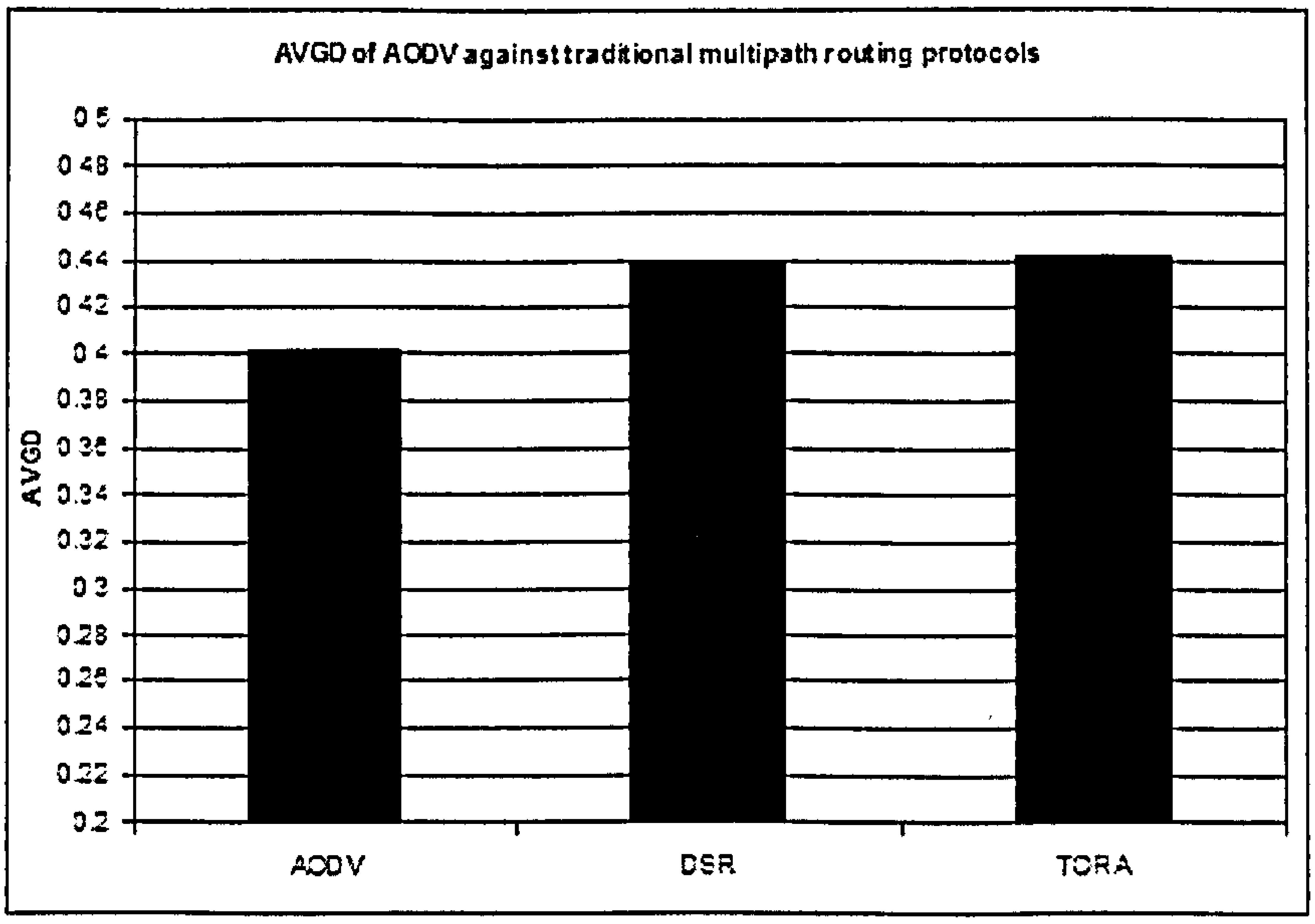

Figure 3.11: Average performance of each protocol in terms of AVGD

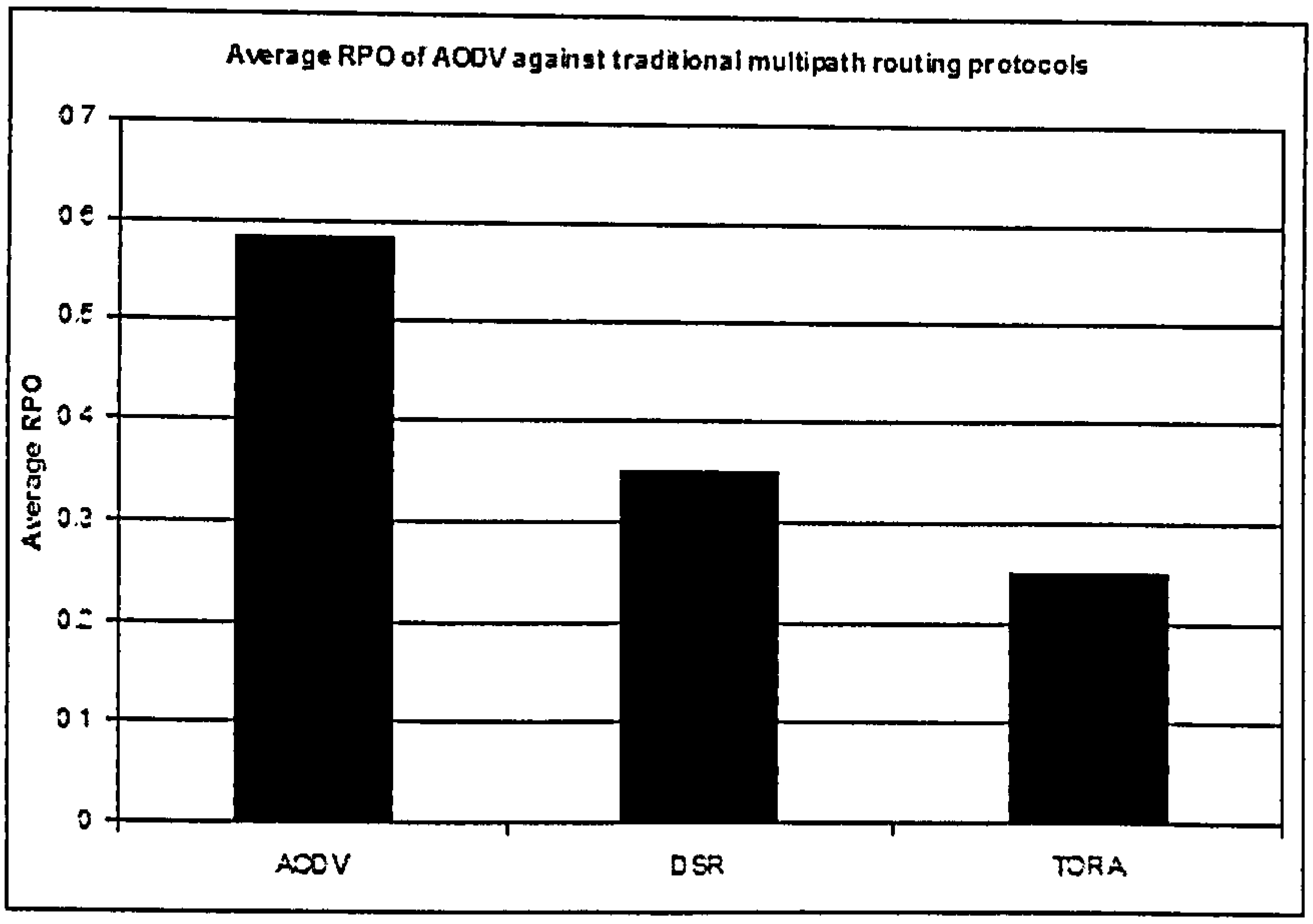

Figure 3.12: Average performance of each protocol in terms of RPO

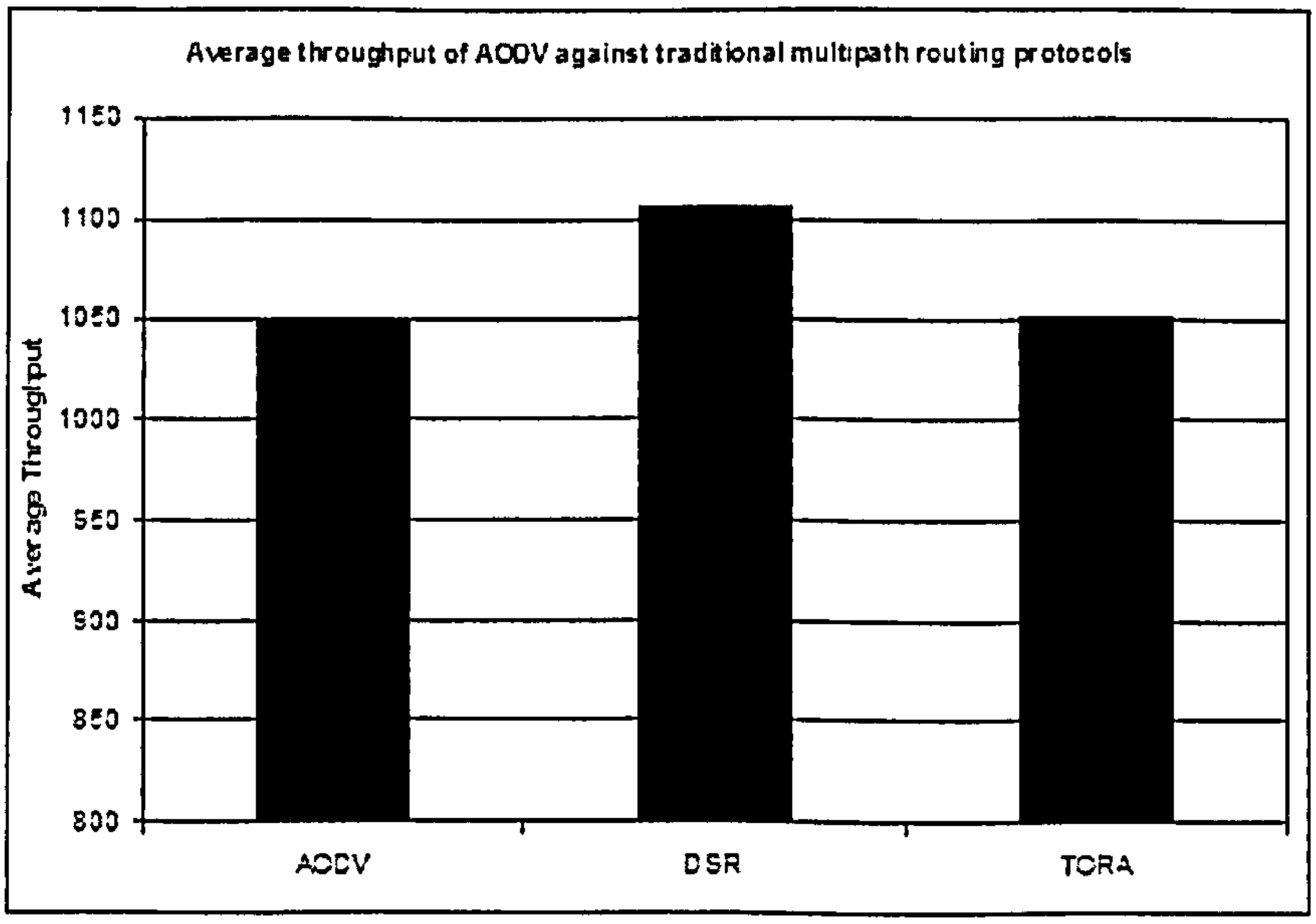

Figure 3.13: Average performance of each protocol in terms of throughput

which is better than both traditional multipath protocols DSR and TORA. As shown by the simulation results, AODV performance has also a good convergence to the performance of traditional multipath protocols DSR and TORA in terms of PDF, RPO, and throughput. Additionally, AODV is a well-proven and well-known as an effective reactive routing protocol in MANETs even with its single path feature.

For these reasons, AODV is a more desirable protocol than the other protocols, especially in the case of high mobility and high traffic load. This means that it is strongly recommended to develop many efficient extensions by combining AODV features with the multipath feature of some traditional protocols. As concluded by the literature review of this thesis, multipath extensions to AODV look more interesting than the extensions to any other traditional protocol in MANETs.

3.5 Related Work of Multipath Extensions to AODV

As mentioned earlier in Chapter 2, single path abstraction is one of the most drawbacks of AODV that are extensively addressed in the recent studies of AODV extensions. Single path abstraction requires a source node to re-establish a new RDP when detecting a link failure in the primary current route.

In traditional AODV, a RDP is invoked on-demand whenever the current route fails due to a link failure. A RMP starts by sending a RERR packet throughout the network. When a link failure is detected, a RERR is sent to all nodes related to that link to update their routing tables. In such case, a new RDP is invoked to obtain an alternative route. AODV selects only a single route (the optimal route) from all routes that are detected during a RDP. The mechanism of AODV increases frequent route rediscovery attempts and consequently increasing delay and control overhead.

Many approaches are conducted to solve this problem of AODV either partial-route re-establishment or multipath establishment approaches. AODV-BR [105] is an example of re-establishment approaches that try to find a partial-route as a backup when the routing protocol detects a broken link in the primary current route. Backup route is maintained at each neighbour of the primary current route to be used when needed. AODV-BR has a drawback of the limit number of routes.

MNH approach [124] is another extension to AODV. It is an example of multiple-route establishment extensions that keeps track all of nodes that send RREQ messages and wait for RREPs. In case of receiving multiple RREP messages from multiple nodes, multiple routes can be detected. However, number of routes that MNH can detect is very small, because MNH does not take into consideration waiting time needed to receive all possible RREPs. So, MNH can miss some efficient routes in routing tables and consequently it launches a RDP frequently, which leads to more routing overhead.

AOMDV [17] is another example of multiple-route establishment extensions to AODV. AOMDV detects multiple loop-free and link-disjoint routes. A notion of advertised-hop-count is used to guarantee loop-freedom of a route. In order to produce link-disjoint routes, a strong restriction is applied to route discovery process in AOMDV by the first-hop field in a RREQ packet, which is compared to the first-hop-list in a routing table. A vital drawback of AOMDV is that many efficient routes can be missed due to the restriction of link-disjoint routes, which leads to consume too much memory with increasing in routing overhead. Another drawback with AOMDV is that it deletes links when they seem to have failed. The protocol sometimes considers congested links as broken links, and thus highly congested paths are removed by AOMDV mechanism.

AODVM [89] is another extension to AODV, which produces multiple routes with only node-disjoint feature. However, AODVM consumes too much memory with increasing in routing overhead because the node-disjoint restriction still produces inefficient routes.

A recent extension to AODV is MRAODV [13] which is considered a non-disjoint multipath protocol. MRAODV reduces routing overhead by extending the waiting time of RREPs until detecting all possible routes included by all RREPs. In addition, MRAODV connects the separated reverse path fragments to help increasing number of multiple routes. However, MRAODV mechanism tends to wait for long time to check if there are more available routes including inefficient routes. Furthermore, receiving so many routes consumes more memory and requires more search time to find out the alternative route among large number of routes stored in routing table.

Most recent multipath extensions to AODV are the Two Hops Backup Routing (2HBR) [125] and AODV with Meshed Multipath (AODV-MM) [126]. The approach of 2HBR focuses on the RMP by detecting two hops alternative routes in case of a link failure. However, it leads to the original AODV performance if there is a failure in the backup route itself. In AODV-MM, 2HBR is extended and modified to improve packet delivery ratio by building meshed multiple alternative routes when receiving RREP packets. Like all the previous work, 2HBR and its extension, AODV-MM, do not take into account the efficiency of the routes. They are interested only in the increasing the number of alternative routes regardless of their efficiency.

3.6 Simulation-Based Evaluation of AOMDV and MRAODV

In this section, two multipath extensions to AODV, namely AOMDV and MRAODV are evaluated against AODV and the two traditional multipath protocols DSR and TORA. Evaluation is accomplished for all protocols under the same environment of the simulation mentioned earlier in this chapter. The same performance metrics and input parameters are used here again to evaluate multipath protocols in MANETs. Simulations are carried out using NS2 version 2.26 on Linux platform - Fedora 5 with the same mobility models and traffic scenarios described earlier in details in this chapter.

The mechanisms of AOMDV and MRAODV are presented later in Chapter 4. For MRAODV simulations, the implementation of AOMDV is modified by extending the RREP waiting time parameter to 20 seconds instead of 1 second in AOMDV simulations. The time of 20 seconds is the average waiting time measured during the simulation when reaching to the average maximum number of multiple routes. As the implementation of AOMDV which is involved by NS2.26 is applied also to MRAODV, this means that MRAODV is simulated as a link-disjoint version of the original MRAODV because of the link-disjoint feature associated with the implementation of the original AOMDV itself.

3.6.1 MRAODV against AOMDV

By comparing the two multipath extensions to AODV, AOMDV and MRAODV, Figure 3.14 illustrates a comparison between AOMDV and MRAODV in terms of PDF. The simulation results show that MRAODV outperforms AOMDV in high and medium scenarios. As shown by the figure, the performances of the two protocols converge at the low mobility scenarios.

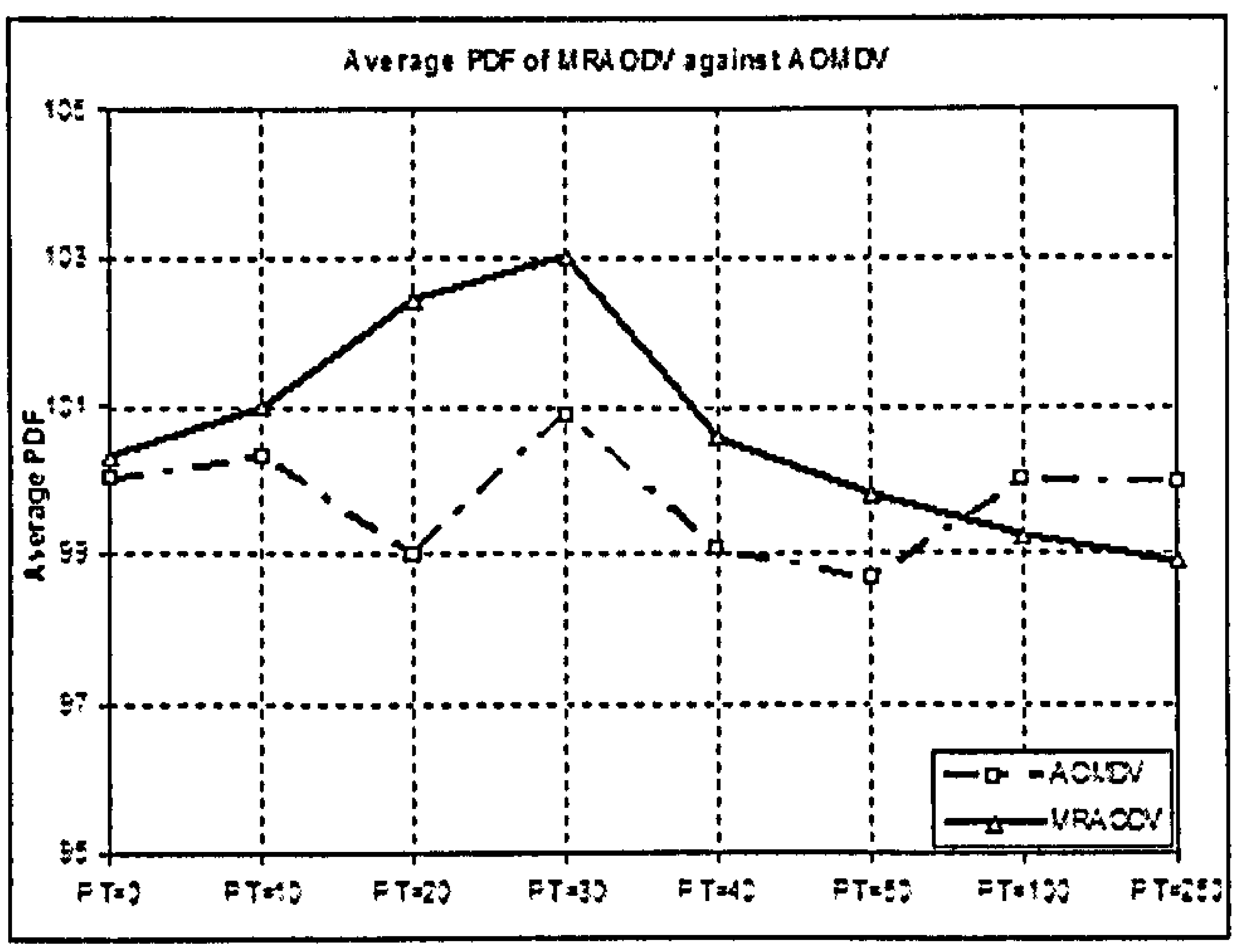

Figure 3.14: Average PDF of MRAODV against AOMDV

Figure 3.15 illustrates a comparison between AOMDV and MRAODV in terms of average end-to-end delay. Simulation results show that AOMDV has better performance than MRAODV in terms of AVGD in all mobility scenarios. As shown by the figure, the performance of MRAODV converges to AOMDV performance at the medium mobility scenarios.

Figure 3.16 illustrates a comparison between AOMDV and MRAODV in terms of RPO. Simulation results show that MRAODV has less routing packets overhead

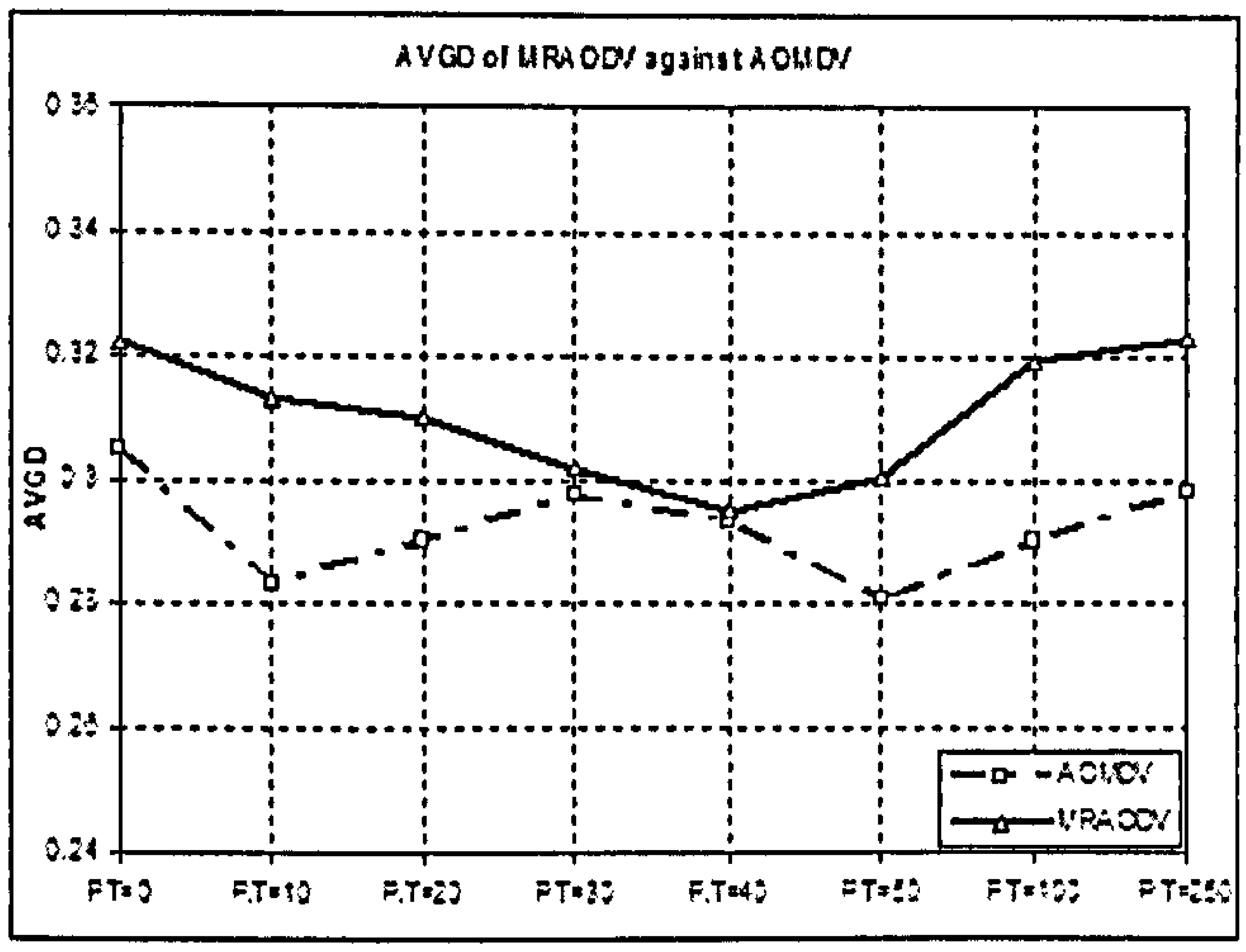

Figure 3.15: Average end-to-end delay of MRAODV against AOMDV

than AOMDV in high and medium mobility scenarios. As shown by the figure, the performances of the two protocols converge at the low mobility scenarios.

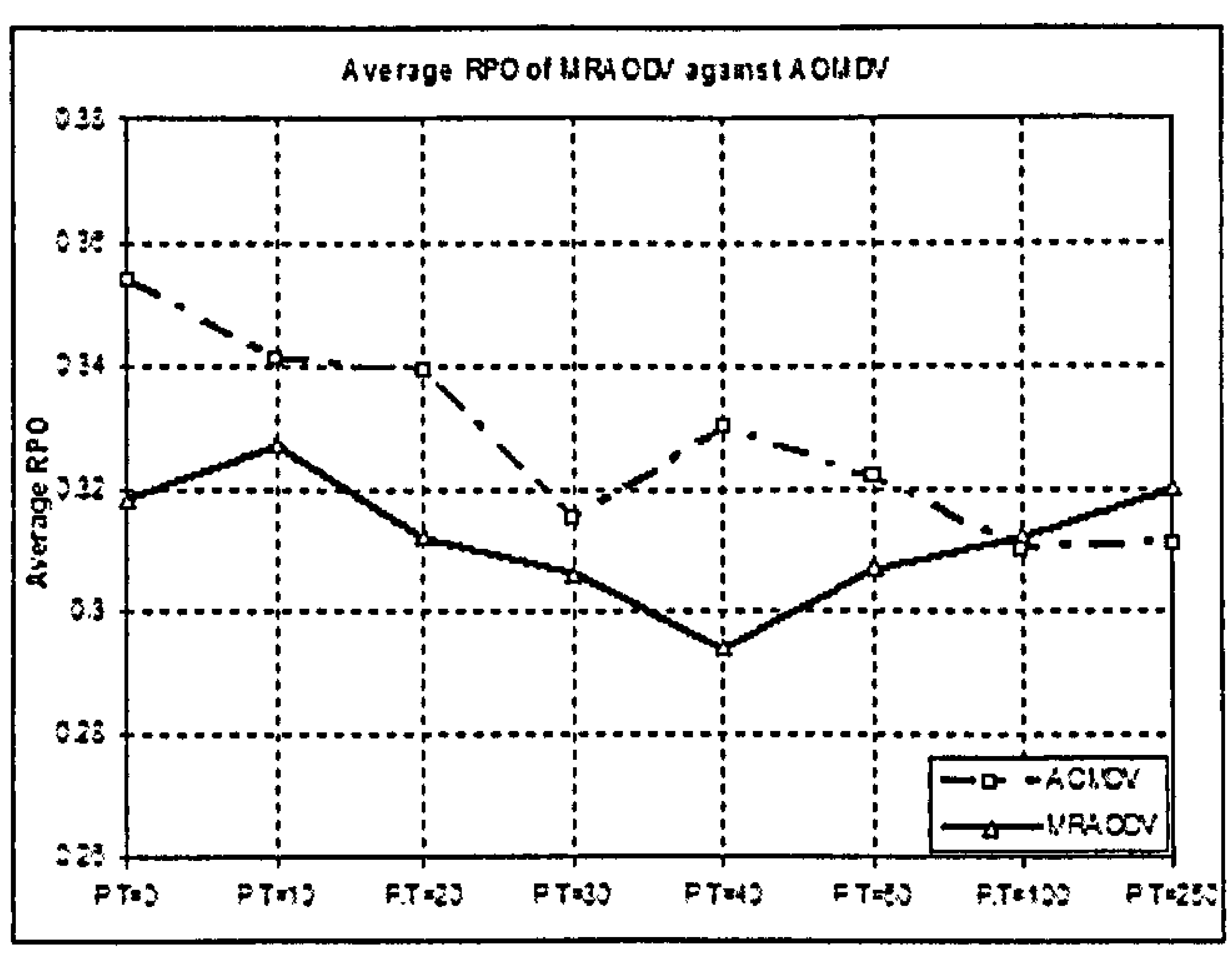

Figure 3.16: Average RPO of MRAODV against AOMDV

Figure 3.17 illustrates a comparison between AOMDV and MRAODV in terms of throughput. Simulation results show that MRAODV outperforms AOMDV in high mobility scenarios while AOMDV outperforms MRAODV in low mobility scenarios. As shown by the figure, the performances of the two protocols converge at the medium mobility scenarios.

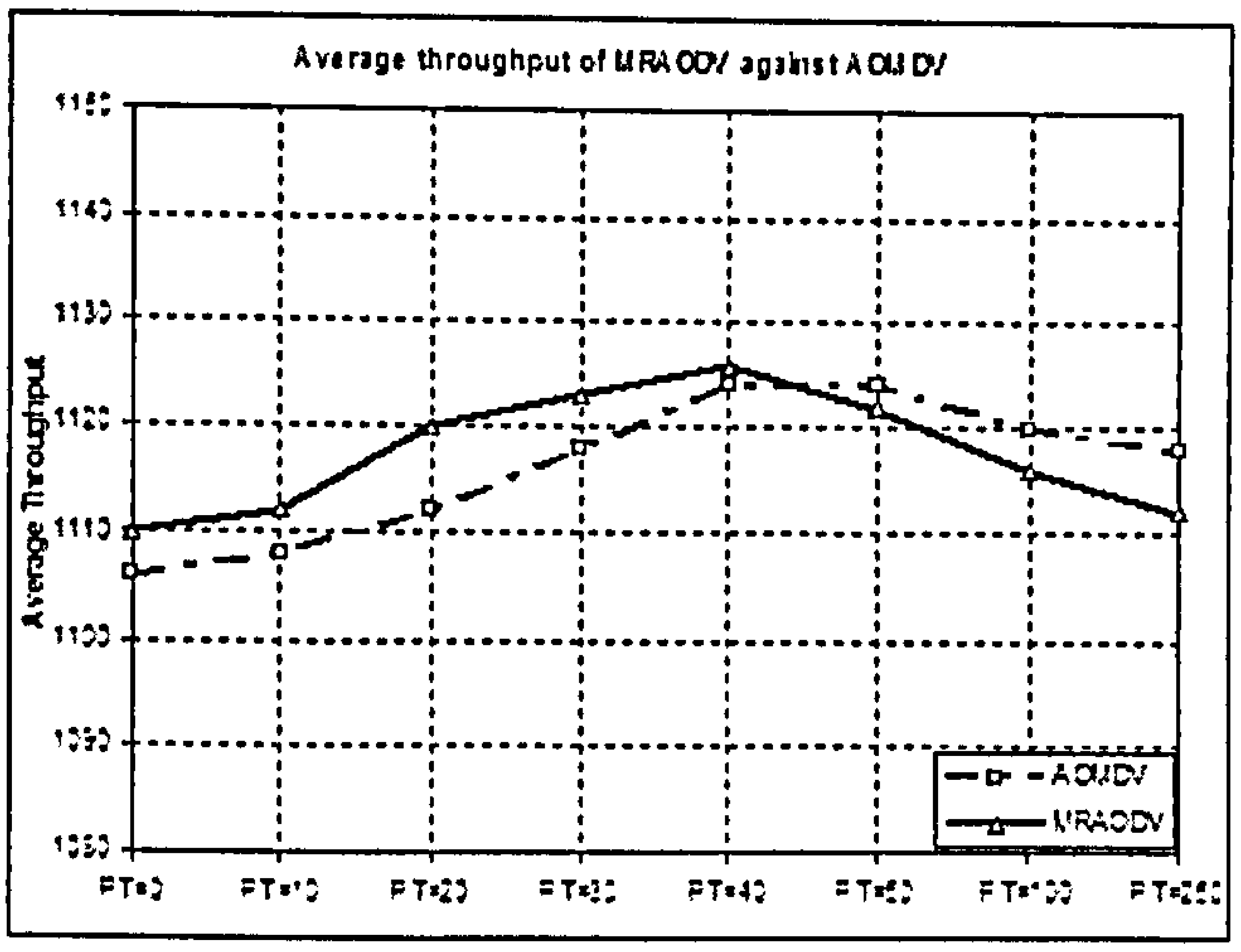

Figure 3.17: Average throughput of MRAODV against AOMDV

As shown in the last four figures, MRAODV outperforms AOMDV in terms of all performance metrics except AVGD. It is clear from the figures that the performances of AOMDV and MRAODV sometimes converge to each other which can be justified by the mechanism and the implementation of MRAODV which is just a modification of the mechanism of AOMDV. As mentioned earlier in this chapter, MRAODV is implemented by extending the waiting time of RREP process in AOMDV implementation.

3.6.2 MRAODV and AOMDV against traditional multipath protocols

As shown in Figures 3.18 and 3.19, MRAODV and AOMDV perform well compared to DSR and TORA in terms of packet delivery fraction and throughput in all mobility scenarios. Figure 3.20 shows that AOMDV and MRAODV outperform both DSR and TORA in terms of average end-to-end delay for all mobility scenarios while their performances are less compared to TORA in terms of RPO during different scenarios of mobility which is shown clearly in Figure 3.21.

A significant conclusion of these results is that AOMDV and MRAODV have better average of performance in terms of all performance metrics except RPO as shown in Figure 3.21, and this is why we still need to develp a new extension to AODV. Another significant conclusion is that MRAODV has less performance than AOMDV in terms of AVGD. Because of the significant of these two conclusions, they are discussed again later in the next section.

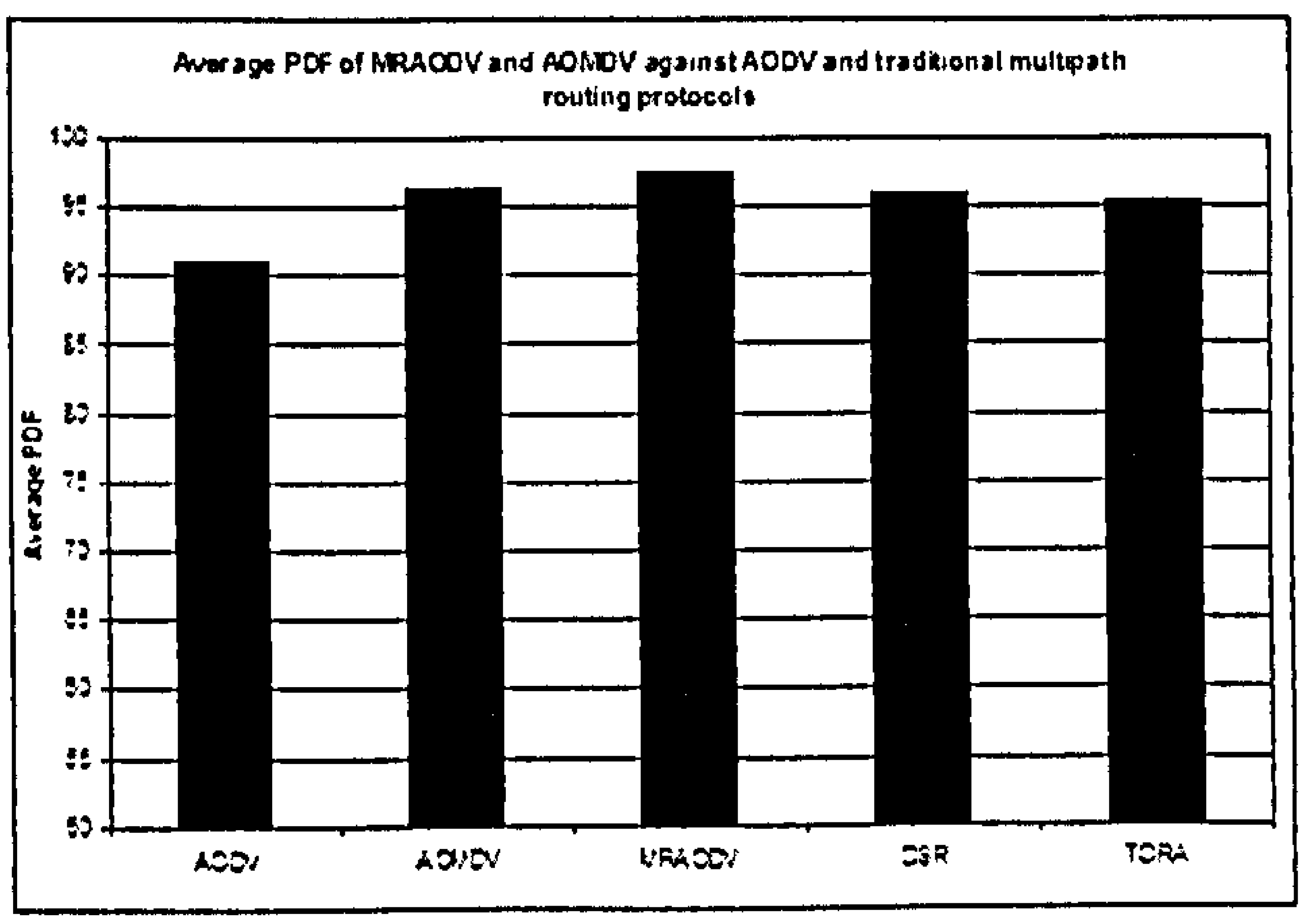

Figure 3.18: Average PDF of AOMDV and MRAODV against DSR and TORA protocols

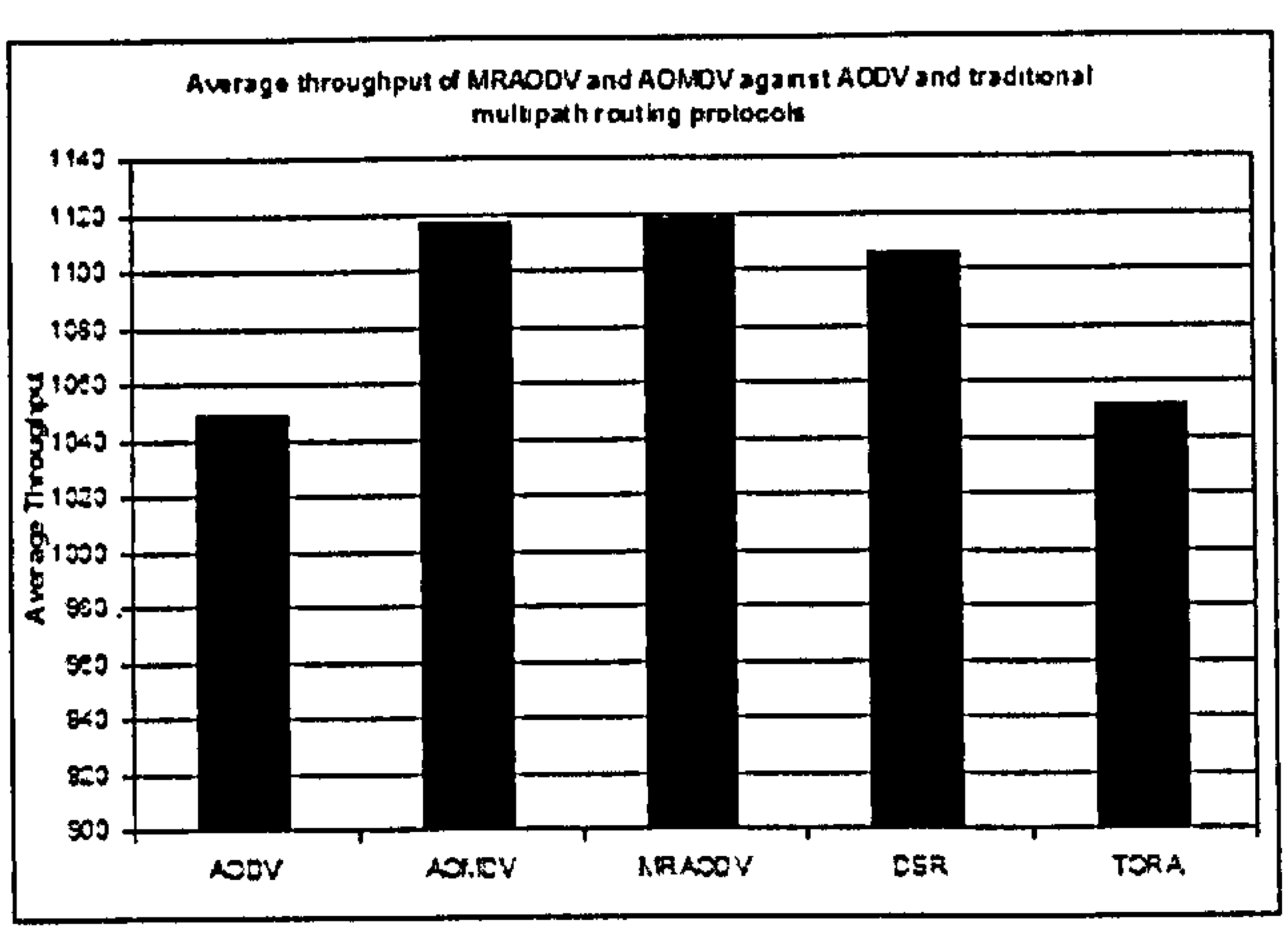

Figure 3.19: Average throughput of AOMDV and MRAODV against DSR and TORA protocols

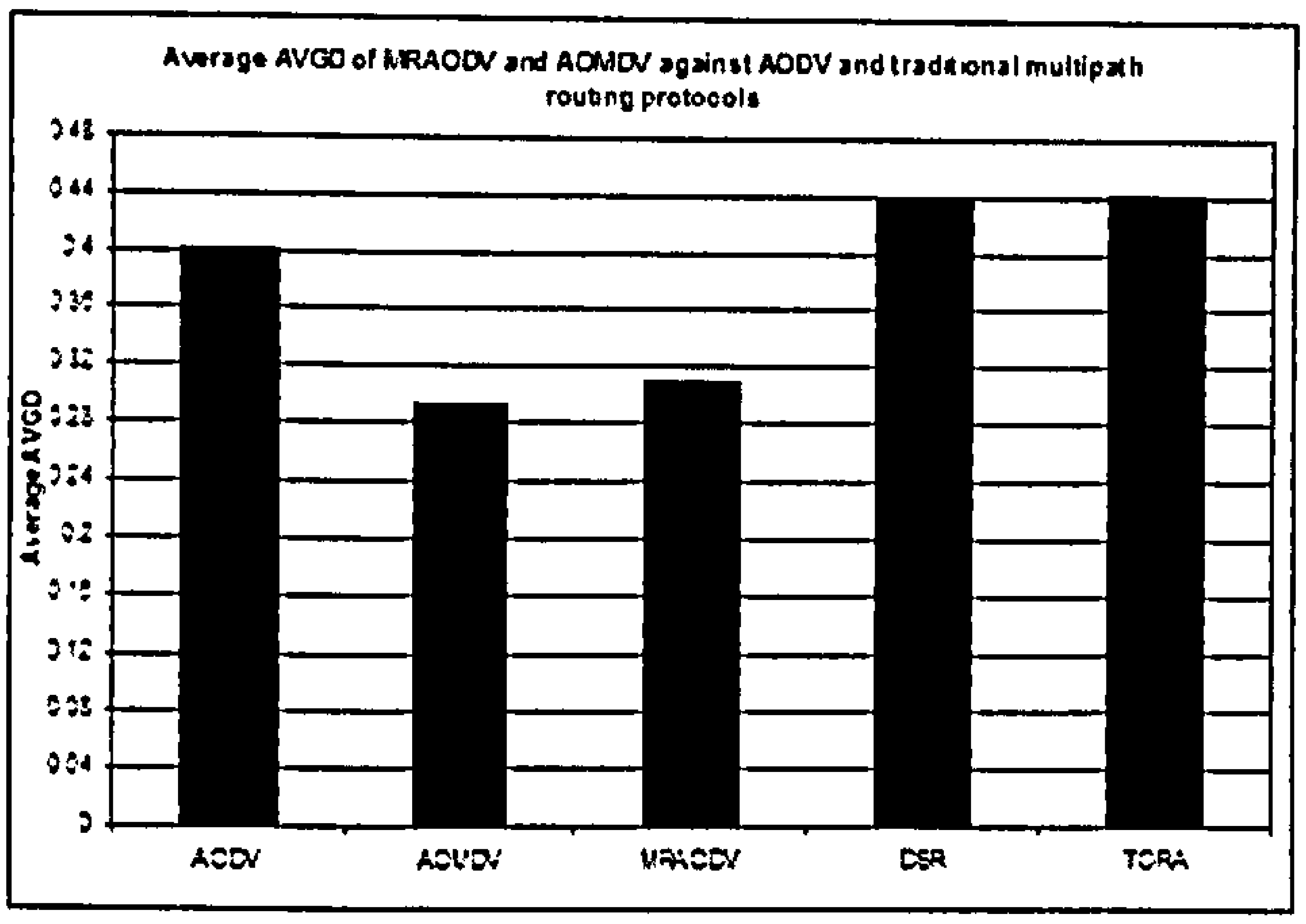

Figure 3.20: Average end-to-end delay of AOMDV and MRAODV against DSR and TORA protocols

3.7 General Discussion

In this section, simulation results of AOMDV prove that multipath extensions to AODV perform well comparing to traditional multipath protocols in MANETs; DSR and TORA. Simulation results show the average performance of AOMDV against AODV and traditional multipath routing protocols DSR and TORA. It is shown that AOMDV generally outperforms the single path version of AODV and both multipath protocols DSR and TORA. For this reason, a recent multipath extension to AODV; MRAODV is simulated and evaluated against DSR and TORA to determine the starting point of this research, which is determined later as developing a new multipath extension to MRAODV.

As shown in the simulation results, MRAODV has the highest overall performance amongst the compared multipath protocols including AOMDV and traditional multipath protocols DSR and TORA in terms of the overall PDF and throughput. MRAODV also outperforms AOMDV and DSR in terms of the overall RPO. A significant result here is that both AOMDV and MRAODV have better average performance compared to the traditional multipath protocols in terms of all performance metrics except RPO which is still better in traditional protocol TORA. In addition, even though that MRAODV enhances the RPO in AOMDV to a certain extent, a

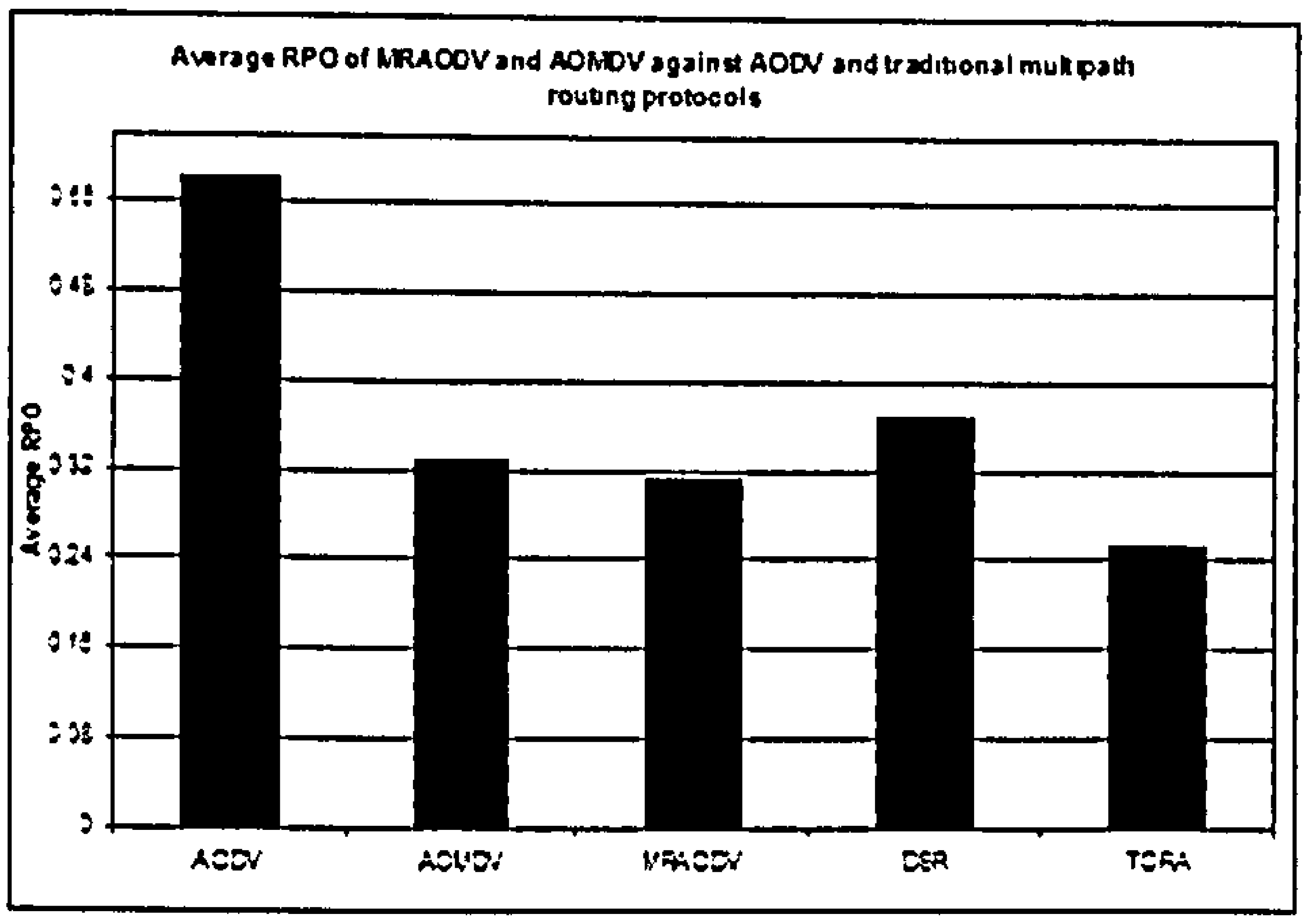

Figure 3.21: Average RPO of AOMDV and MRAODV against DSR and TORA protocols

vital drawback in AVGD is appeared in MRAODV. Instead of enhancing AVGD in AOMDV, the performance of MRAODV is reduced compared to AOMDV.

For these reasons, MANETs still need a new extension to AODV which can develop MRAODV so that the new extension should solve the drawbacks of MRAODV. Hence, the starting point of this research is determined as developing a novel approach called TRAODV which is conducted as a link-disjoint extension to MRAODV. While MRAODV extends the waiting time of RREP until receiving all possible routes by the source node including efficient and inefficient routes, TRAODV varying the waiting time until receiving threshold number of efficient routes, which are only the routes that are stored in the routing table of the source node. TRAODV approach is described in details later in Chapter 4.

Chapter 4

Threshold Efficient Multiple Routes in AODV (TRAODV Approach)

4.1 Introduction

Most multipath extensions to AODV aim to detect large number of multiple routes regardless of the *route efficiency*. In such extensions, a large percentage of *inefficient routes* is associated with the route discovery process leading to a higher routing overhead. On the other hand, resource consuming is considered a challenge in MANETs so that a routing protocol should deal with the end-to-end delay, network bandwidth, and memory consuming which are affected by storing and employing a large percentage of inefficient routes.

In contrast, several multipath extensions to AODV utilise Route Reply (RREP) timeout used in traditional AODV, which is insufficient to detect all possible routes, and consequently many *efficient routes* can be missed due to the short period of the RREP timeout. Some approaches extend the RREP timeout to detect all possible routes however, they employ too long a period so that many efficient routes that are detected early become inefficient due to the mobility of the nodes, which leads to increase link failure occurrence in these routes. Thus, instead of storing the routes in a routing table for long time while waiting for more arrival routes, the efficient routes should be utilised by the source node as soon as possible to minimise the effect of nodes' mobility on the efficient routes.

In the experimental study presented in Chapter 3, two existing multipath extensions to AODV, namely AOMDV and MRAODV are evaluated against two traditional multipath protocols in MANETs, namely DSR and TORA in order to narrow down the starting point of the research. Simulation results of this experimental study show that both AOMDV and MRAODV have some drawbacks in their performances compared to the traditional multipath protocols, especially in terms of the routing packets overhead which is still better in the traditional protocol TORA even though that MRAODV enhances the routing packets overhead compared to AOMDV to a certain extent. Additionally, a crucial drawback is associated with MRAODV performance with regard to the average end-to-end delay. Instead of enhancing the average end-to-end delay, a recession is observed in the performance of MRAODV which is reduced compared to the performance of AOMDV. For these reasons, a new multipath extension to AODV is developed in this chapter to overcome the drawbacks of the previous extensions AOMDV and MRAODV.

This chapter presents our first novel approach called Threshold Efficient Multiple Routes in AODV (TRAODV) which is developed in this thesis as a new extension to AODV protocol in MANETs. TRAODV is considered a link-disjoint multipath establishment routing approach, which tries to improve Route Discovery Process (RDP) in multipath AODV by extending the waiting time required to receive all RREPs in the RDP taking into account the time required to detect *threshold* number of efficient routes. TRAODV is considered a link-disjoint extension to the existing protocol MRAODV [13], which is in turn a recent extension to Multiple Next Hops (MNH) protocol [124], a direct extension to traditional AODV.

In the beginning of the chapter, the routing mechanism of AODV protocol is presented and analysed aiming at showing the changes that have taken place in single path mechanism of AODV to implement the multipath mechanism of multipath extensions of AODV such as AOMDV, MRAODV, and TRAODV. Then, a related work review of multipath routing in AODV is introduced and finally, TRAODV approach is presented. A result study of TRAODV simulation using NS2 is presented later in Chapter 7 with an evaluation of TRAODV performance against the performances of AOMDV, MRAODV, DSR, and TORA protocols.

4.2 Routing Mechanism in AODV

Based on the fact that AODV is a single path reactive protocol, nodes compute routes in AODV only when they are needed and one route only is selected at the moment of receiving the routes. Each received route is compared to the current primary route to determine which one is better based on some predetermined selection criteria [12]. Similar to all routing protocols in MANETs, AODV has two main phases RDP and RMP. This section focuses on the mechanisms of these two main phases in AODV routing protocol.

4.2.1 RDP mechanism in AODV

In AODV, the source node invokes a RDP by flooding a RREQ packet in the network when a route is not available for the destination. It may obtain multiple routes to different destinations from a single RREQ. The major difference between AODV and other on-demand routing protocols is that it uses a Destination Sequence Number (DestSeqNum) to determine an up-to-date path to the destination. A node updates its path information only if the DestSeqNum of the current packet received is greater than the last DestSeqNum stored at the node. A RREQ carries the Source IDentifier (SrcID), Destination IDentifier (DestID), Source Sequence Number (SrcSeqNum), DestSeqNum, Broadcast IDentifier (BcastID), and finally the Time To Live (TTL) field. The field DestSeqNum indicates the freshness of the route that is accepted by the source node [12][2][8]. Steps of RDP mechanism in AODV are summarised as follows:

- When a source node decides to communicate a destination node, it sends a RREQ message to its neighbours.
- On receiving the RREQ message by an intermediate node, it either forwards it or prepares a RREP packet if it has a valid route to the destination.
- All intermediate nodes that have valid routes to the destination, or the destination node itself, are allowed to send RREP packets back to the source node

via the Intermediate nodes.

- When an intermediate node receives a RREP packet, information about the previous node from which the packet was received is also stored in order to forward the data packet to this next node as the next hop toward the destination.

For instance, suppose the following example shown in Figure 4.1 for RDP in AODV which explains the process of sending a RREQ from a source node S to a destination node D and retransmits RREP from the destination node to the source node. Steps of RDP mechanism in AODV are summarised for this example as follows:

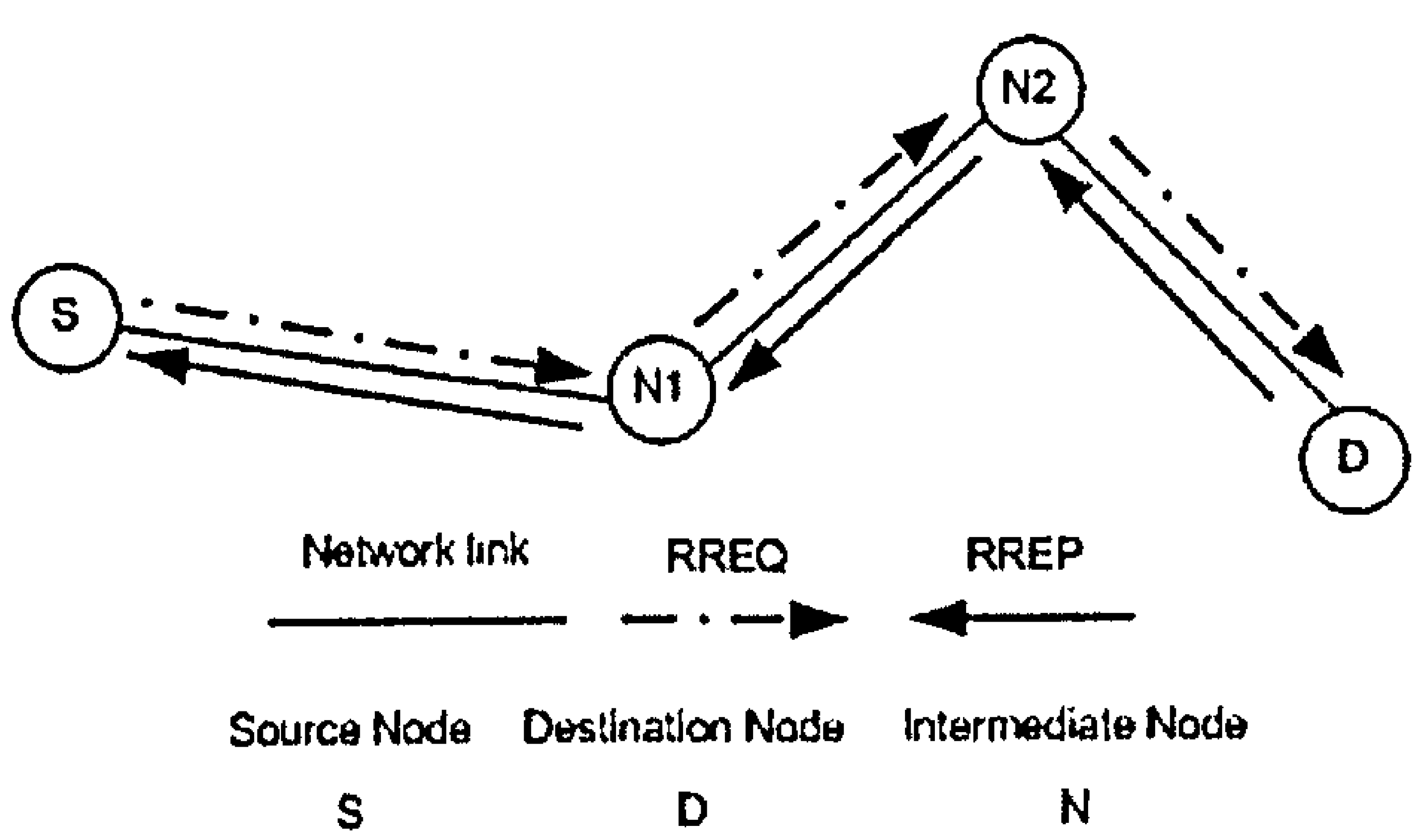

Figure 4.1: RDP in AODV routing protocol

- The source node S initiates a route discovery process by flooding a RREQ in the network towards the destination node D, assuming that the RREQ contains a destination sequence number and a source sequence number.
- When the intermediate nodes receive the RREQ packet, they check their routes to the destination.
- In case a route to the destination is not available in the intermediate nodes, they forward it to their neighbours.
- If the destination sequence number at an intermediate node is greater than the others, then only this node is allowed to reply along the stored route to the

source. This is because this node has a more recent route to the destination (it has greater destination sequence number).

- If the RREQ reaches the destination (node D) through a particular route or any other alternative route, the destination also sends a RREP to the source using the same route.
- Multiple RREP packets may reach the source node.
- All the intermediate nodes receiving a RREP update their routing tables with the latest destination sequence number of a single route.
- They also update the routing information if it leads to a shorter path between the source and the destination.
- All detected routes are discarded except the optimal route.

Figures 4.2, 4.3, 4.4, 4.5, and 4.6 show the complete procedures of RDP in AODV.

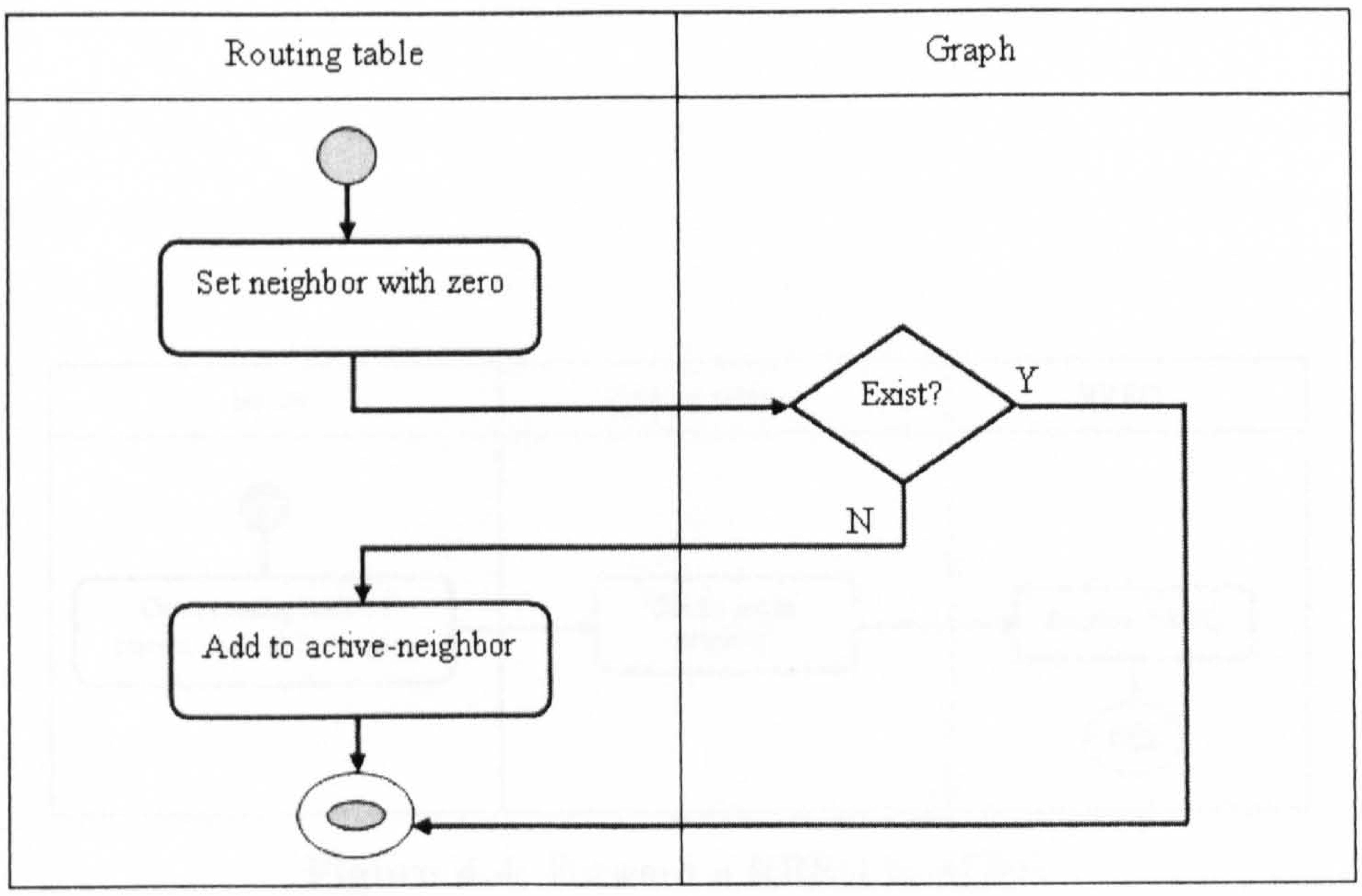

Figure 4.2: Set the neighbours in AODV

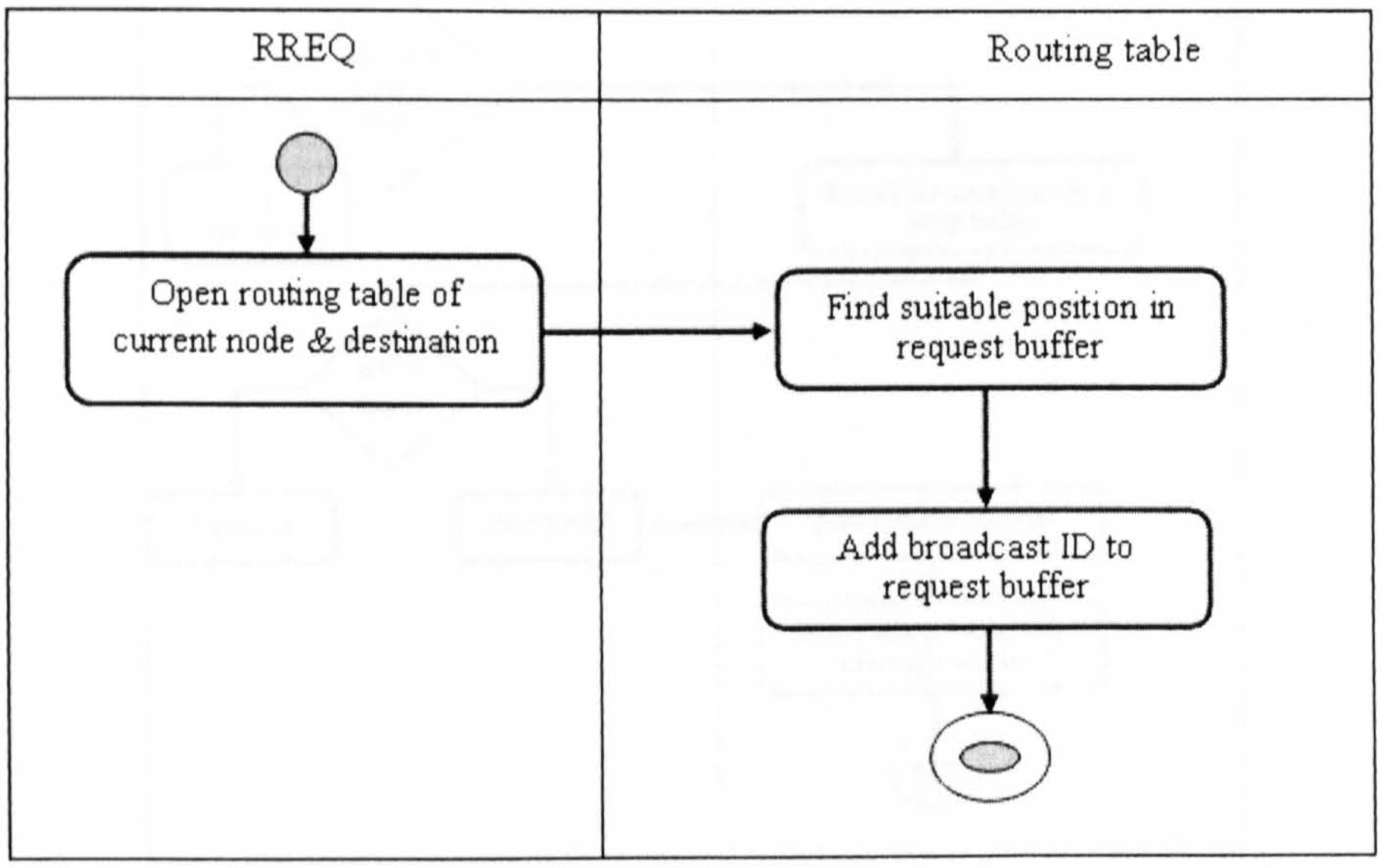

Figure 4.3: Send RREQ to neighbours in AODV

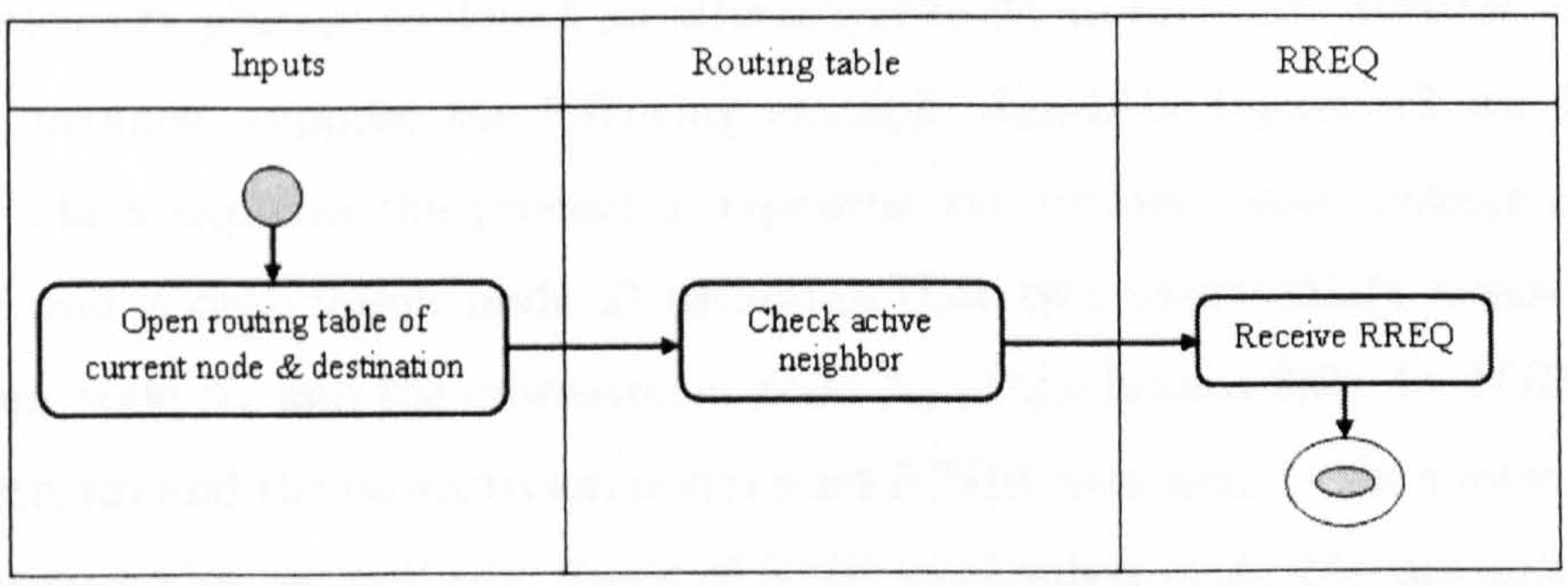

Figure 4.4: Forward a RREQ in AODV

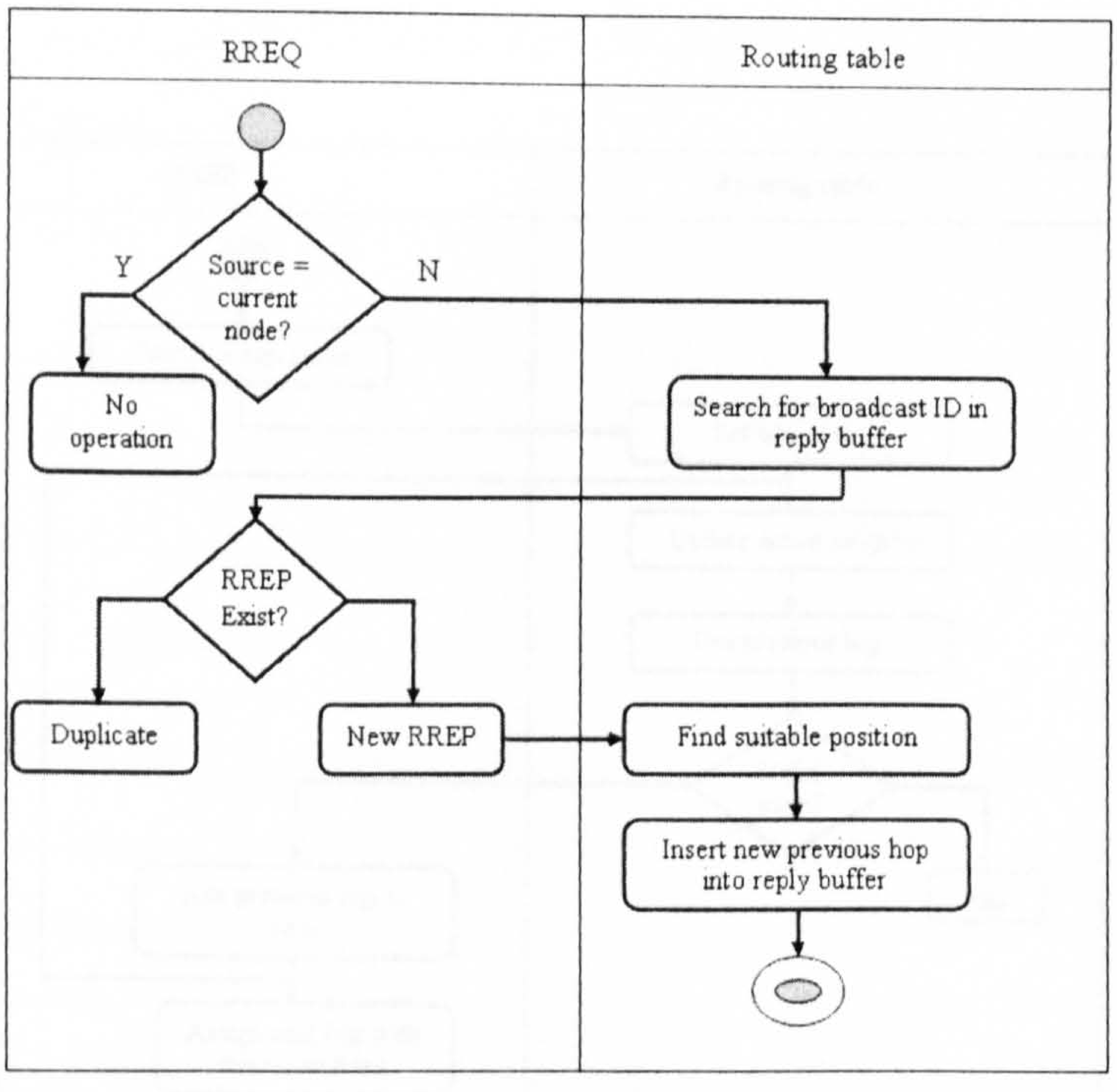

Figure 4.5: Build a reversed path in AODV

4.2.2 RMP mechanism in AODV

AODV uses error messages for route maintenance. When a node detects a broken link to the next hop, it generates a RERR message that contains a list of unreachable destinations and sends it to related nodes. The source node should re-establish a new route discovery process to detect an alternative route to the same destination.

For instance, suppose the following example shown in Figure 4.7 for RMP in AODV which explains the process of repairing the broken route between a source node S and a destination node D assuming that two intermediate nodes are the upstream node N_u and the downstream node N_d of the broken link. In AODV, both the upstream and the downstream nodes send RERR messages to the source and the destination nodes respectively. Steps of RMP mechanism in AODV are summarised for this example as follows:

- The path between the source node S and the destination node D breaks due to a failure of the link connects between the two intermediate nodes N_u and N_d.

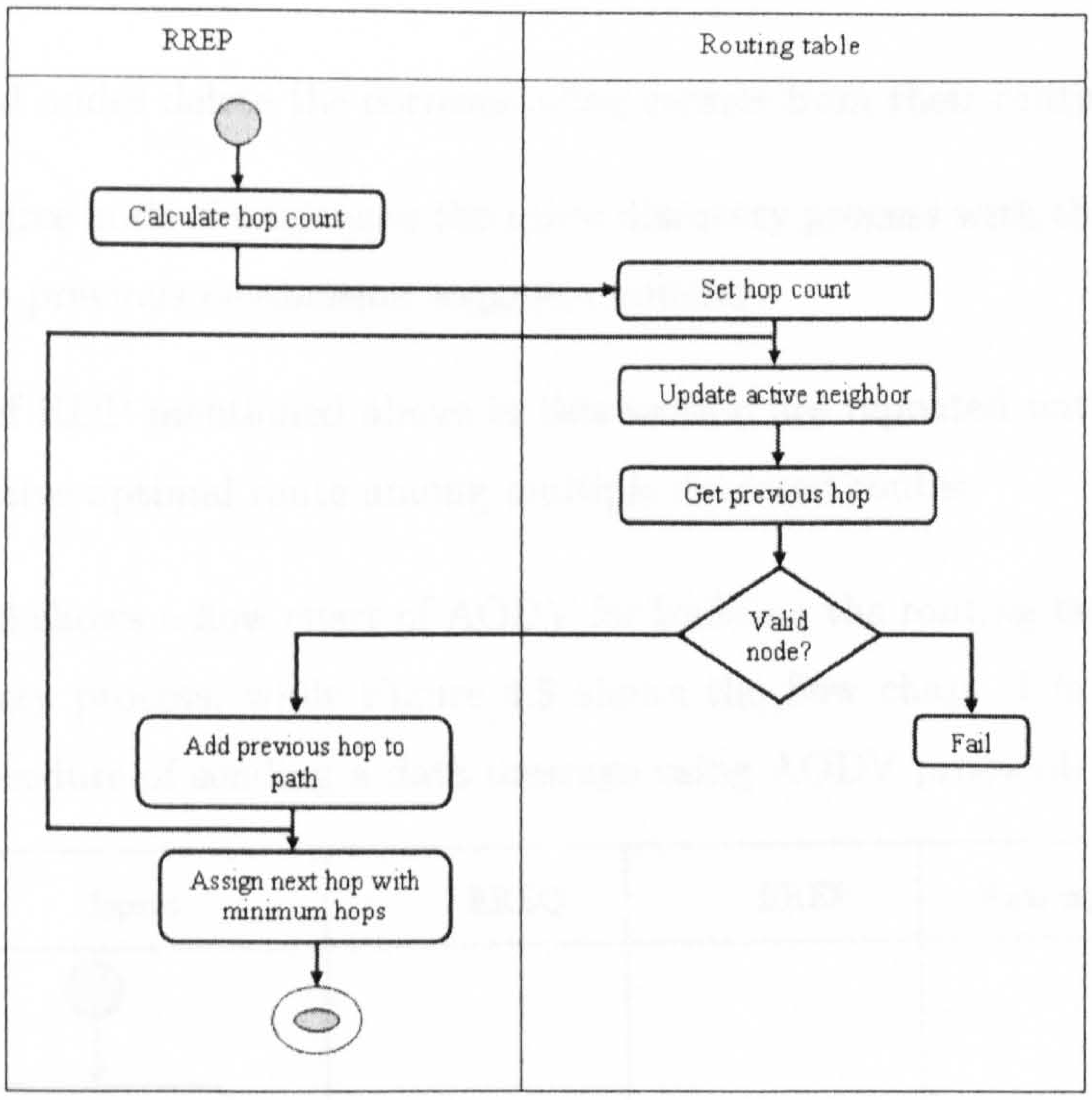

Figure 4.6: Receive a RREP in AODV

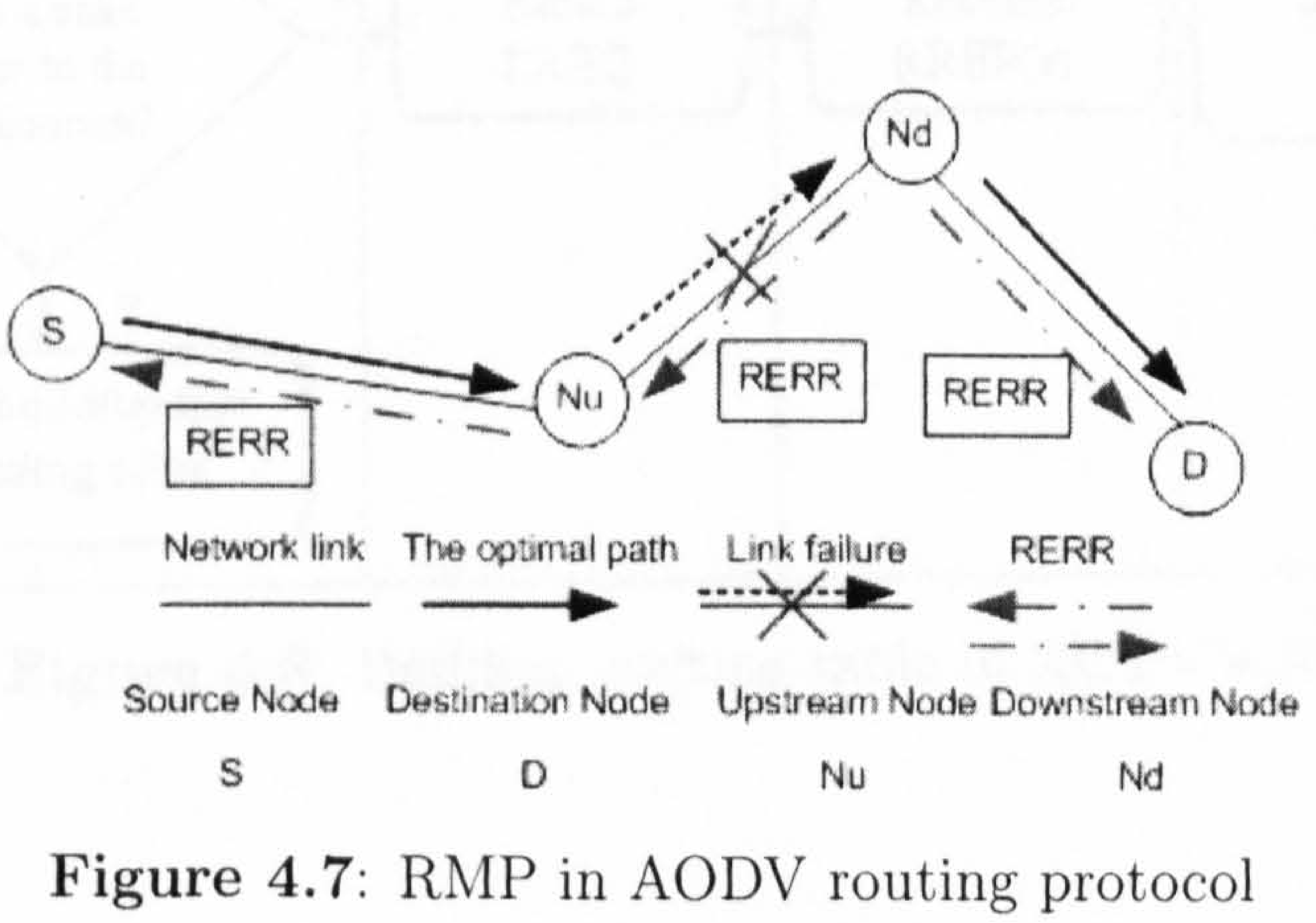

Figure 4.7: RMP in AODV routing protocol

- Both N_u and N_d nodes initiate RERR messages to inform their end nodes about the link break.
- The end nodes delete the corresponding entries from their routing tables.
- The source node S reinitiates the route discovery process with the new BcastID and the previous destination sequence number.
- Steps of RDP mentioned above in this section are repeated until selecting the alternative optimal route among multiple detected routes.

Figure 4.8 shows a flow chart of AODV for building the routing table in AODV's route discovery process, while Figure 4.9 shows the flow chart of invoking a RMP during a procedure of sending a data message using AODV protocol.

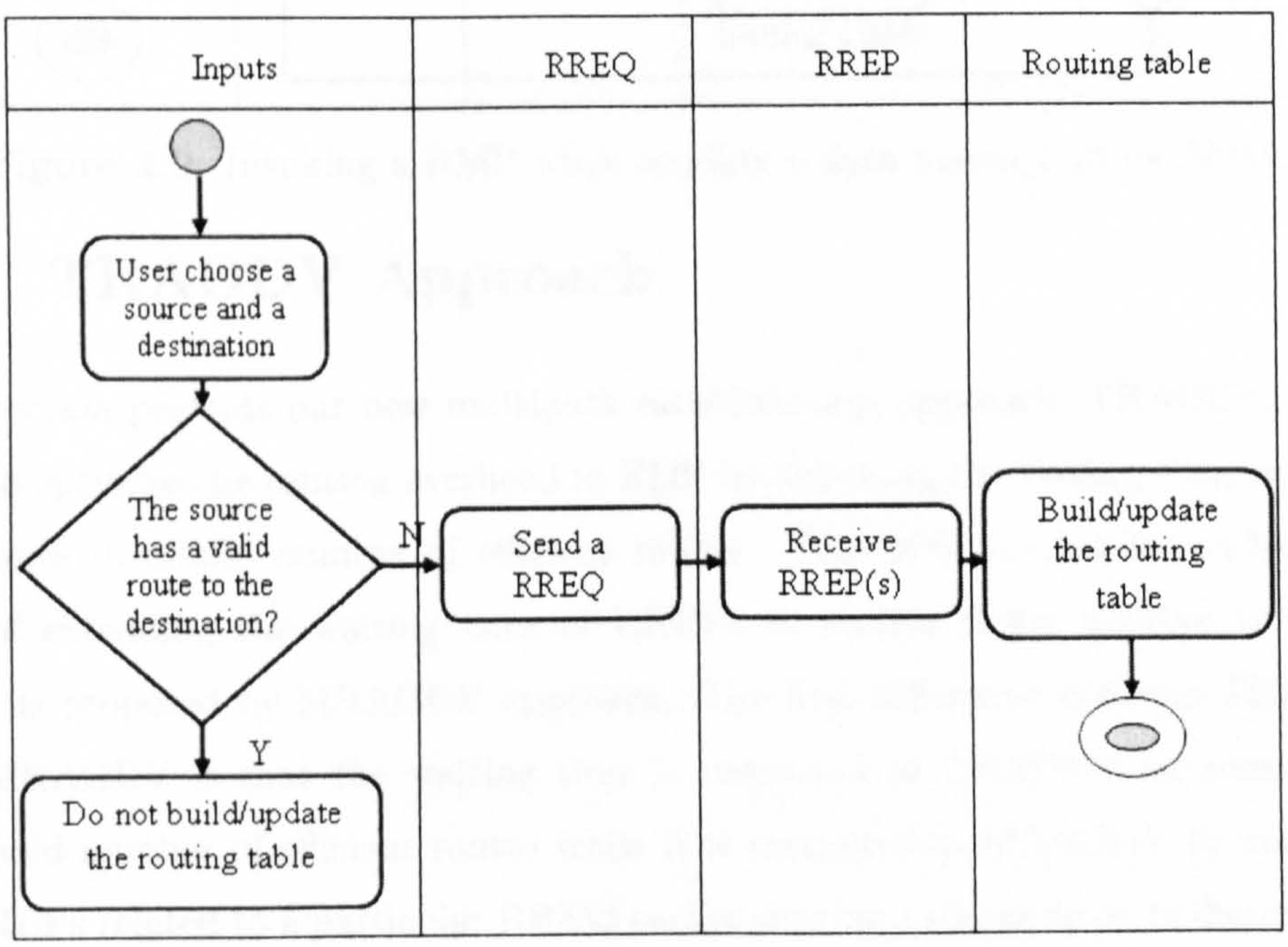

Figure 4.8: Building routing table in AODV's RDP

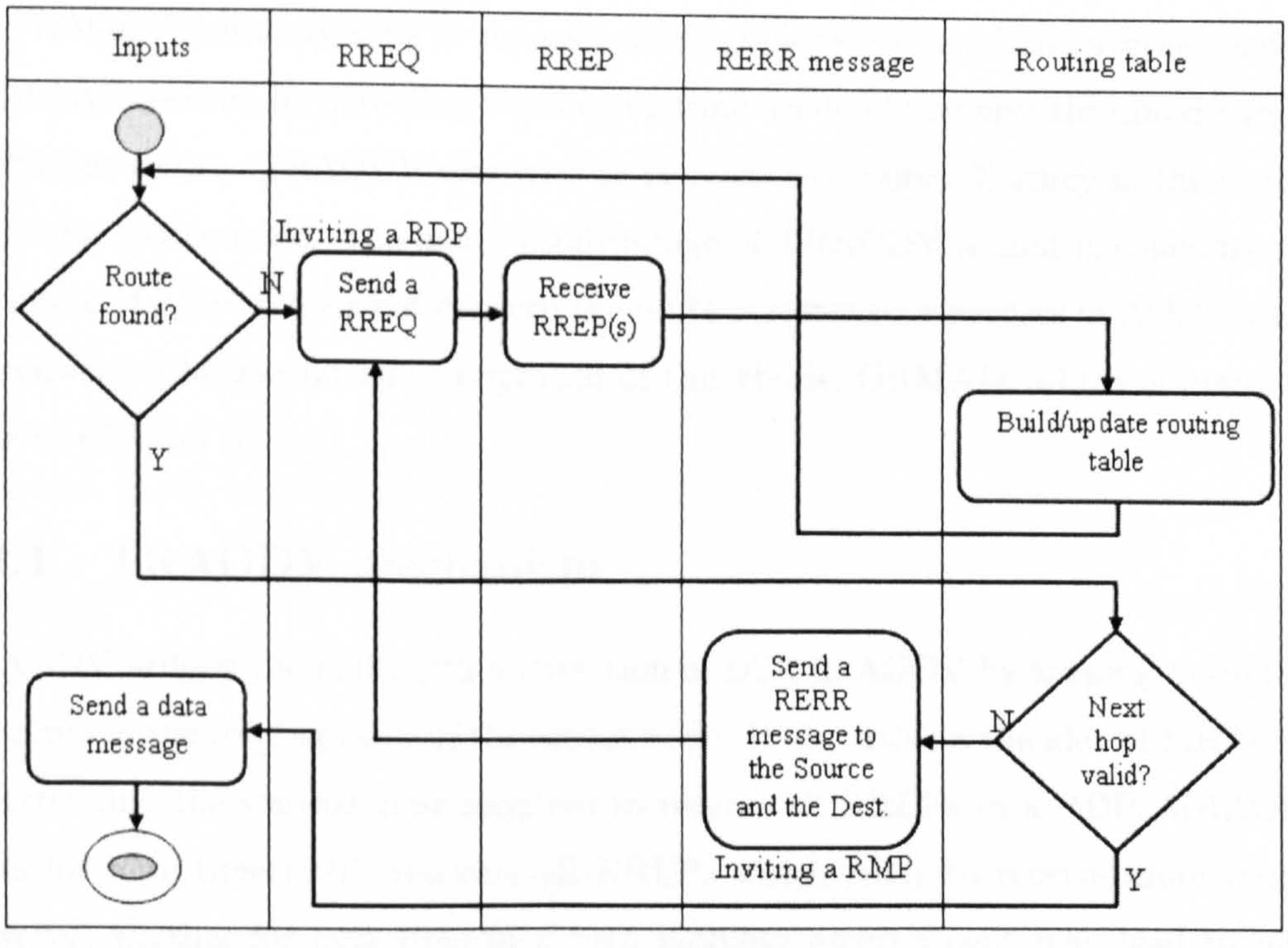

Figure 4.9: Invoking a RMP while sending a data message using AODV

4.3 TRAODV Approach

This section presents our new multipath establishment approach, TRAODV, which tries to optimise the routing overhead in RDP by detecting the waiting time required to receive threshold number of efficient routes. TRAODV mechanism utilises the idea of extending the waiting time of RREPs to receive larger number of routes which is proposed by MRAODV approach. The first difference between TRAODV and MRAODV is that the waiting time is restricted in TRAODV by receiving a threshold number of efficient routes while it is restricted in MRAODV by receiving all RREPs related to a particular RREQ packet sent by a source node to discover the routes to a destination node. The second difference is the nature of the routes that are stored in the routing table and employed for data transmission. TRAODV stores only the efficient routes while MRAODV stores all routes including both efficient and inefficient routes.

TRAODV definitely aims to reduce routing packets overhead and average end-to-end delay overhead by detecting the waiting time needed to receive threshold number of efficient routes. TRAODV also tries to increase the route efficiency in the routing table of a source node. The main disadvantage of TRAODV is that it concerns only the phase of RDP, it does not concern the route maintenance process in AODV which is focused in the second novel approach of this thesis, ORMAD, which is presented later in Chapter 5.

4.3.1 TRAODV mechanism

TRAODV utilises the multipath abstraction of DSR in AODV by keeping more than one route in the routing table of the source node. It also utilises the idea of MRAODV by extending the waiting time required to receive all RREPs in a RDP. MRAODV waits for long time until receiving all RREPs which leads to receive more routes. However, waiting for long time in a high mobility environment may lead to more link failures and consequently more route faults. MRAODV tries to reduce routing delay overhead by detecting the waiting time needed to receive threshold number of efficient routes. Increasing the waiting time may lead to receive more routes which probably include more inefficient routes. TRAODV tries to make a trade-off between receiving as larger number of routes as possible and as less number of inefficient routes as possible.

4.3.2 RDP mechanism in TRAODV

Figure 4.10 shows the mechanism of receiving RREPs during a RDP of TRAODV which is used in the implementation. The mechanism of route discovery process in TRAODV looks like the RDP of the original AODV which is shown earlier in Figure 4.6 with some differences. The first difference in TRAODV is the the waiting time of RREP is extended to T_w, where $T_{min} < T_w < T_{max}$, T_w is the threshold waiting time used by TRAODV, T_{min} is the normal waiting time used by traditional AODV and the extension AOMDV, and T_{max} is the waiting time used by MRAODV to receive all possible RREP packets by the source node. The optimisation method used to find out the threshold T_w is the random search method which is used in TRAODV simulations by varying the waiting time T_w randomly between T_{min} and T_{max} until reaching the threshold number of efficient routes. Threshold number of efficient routes is the global maximum number of efficient routes that can be detected between the two waiting time boundaries T_{min} and T_{max}.

Efficient route selection:

There have been many route selection criteria that are proposed by many routing literatures on MANETs. The most common criteria used in path selection are greater sequence number and less hop count which are used by DSDV proactive protocol, most recent and the shortest path (minimum number of hops) which are used by AODV, and the shortest path only which is used by DSR and TORA. A more recent approach is proposed in [140] in which different selection criteria are used such as link-cost and node-cost. In node-cost selection criteria, the sum of node-cost of all nodes on the route is calculated and assigned as the route cost. Link-cost is similar to node-cost, the sum of link-cost of all links on the route is calculated and assigned as the route cost. One of the most recent approaches of path selection criteria is proposed in [141] which uses a link expiration time and busy rate to calculate the route cost and compares it to a threshold value to decide the degree of traffic in the route. However, this criteria are used for route selection in the routing table. They are not used to determine the route efficiency.

Multiple routes selection in a routing table depending on the path length a weighted is used in some literatures of multipath routing in MANETs. For example, in [142], the weight of a particular path is inversely proportional to the length of the path and for path selection, path longer than 1.2 times the average is ignored. However, this is not mentioned as a precise definition of an efficient route, and additionally it ignores the connectivity factor which certainly affects a route efficiency along with the length of the route.

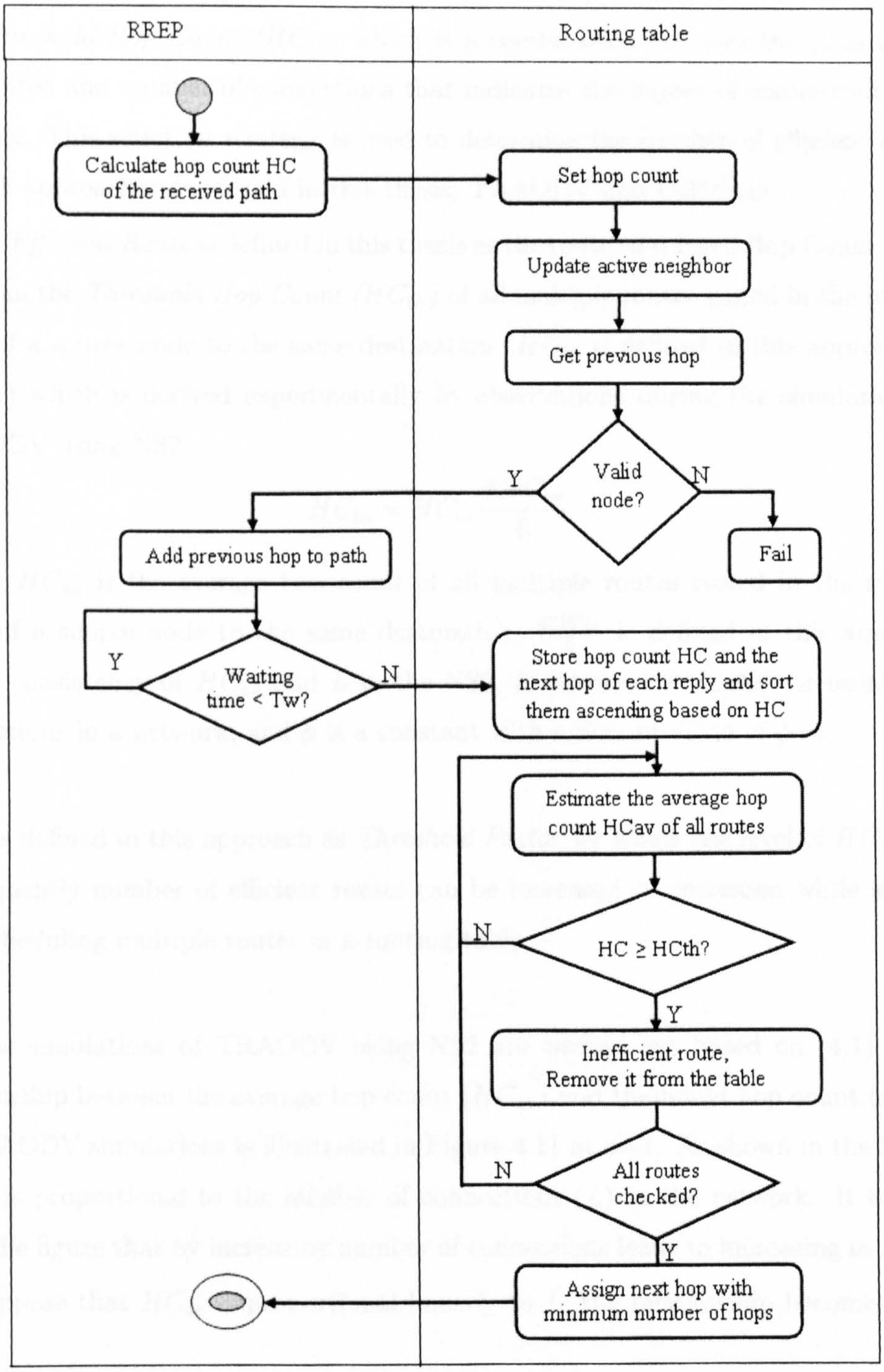

Figure 4.10: Receiving RREPs during the RDP of TRAODV

The selection strategy used in this thesis for multiple efficient routes is based on the *Threshold Hop Count (HC_{th})* which is a combination between the path length a weighted and number of connections that indicates the degree of connectivity in a network. This selection strategy is used to determine the number of efficient routes in both approaches developed in this thesis; TRAODV and ORMAD.

An *Efficient Route* is defined in this thesis as the route that has a Hop Count (HC) less than the *Threshold Hop Count (HC_{th})* of all multiple routes stored in the routing table of a source node to the same destination. HC_{th} is defined in this approach as in (4.1) which is derived experimentally by observations during the simulations of TRAODV using NS2.

$$HC_{th} = HC_{av}\frac{\phi HC_{av}}{L} \tag{4.1}$$

Where HC_{av} is the average hop count of all multiple routes stored in the routing table of a source node to the same destination, $\frac{\phi HC_{av}}{L}$ is defined in this approach as the consistency of HC_{av} and L in the NS2, L denotes to "Links" or number of connections in a network, and ϕ is a constant with a default value of ϕ=1.

ϕ is defined in this approach as *Threshold Factor* by which the level of HC_{th} and consequently number of efficient routes can be increased or decreased while storing and scheduling multiple routes in a routing table.

The simulations of TRAODV using NS2 are carried out based on (4.1). The relationship between the average hop count (HC_{av}) and thrshould hop count (HC_{th}) in TRAODV simulations is illustrated in Figure 4.11 at ϕ=1. As shown in the figure, HC_{av} is proportional to the number of connections (L) in the network. It is clear from the figure that by increasing number of connections leads to increasing in HC_{av}.

Suppose that HC_{av} is proportional linearly to L, the relationship becomes as in (4.2):

$$HC_{av} = KL \tag{4.2}$$

Where K is constant, $K < 1$ because the number of hops in a network is always less than the total number of links.

By substituting HC_{av} from (4.2) into (4.1), HC_{th} can be derived as in (4.3):

$$HC_{th} = \phi K^2 L \tag{4.3}$$

The idea behind the term $\frac{\phi HC_{av}}{L}$ in (4.1) comes from the supposed consistency in the NS2 for the average hop count (HC_{av}) with respect to the number of connections (L). Figure 4.11 shows the consistency of HC_{av} and L during TRAODV simulations. Even though the consistency of HC_{av} and L looks like a constant in Figure 4.11, the value of $\frac{\phi HC_{av}}{L}$ is approximately fixed in a very small range of values between 0.39 and 0.45 at ϕ=1, which is scaled and ilustrated by Figure 4.12.

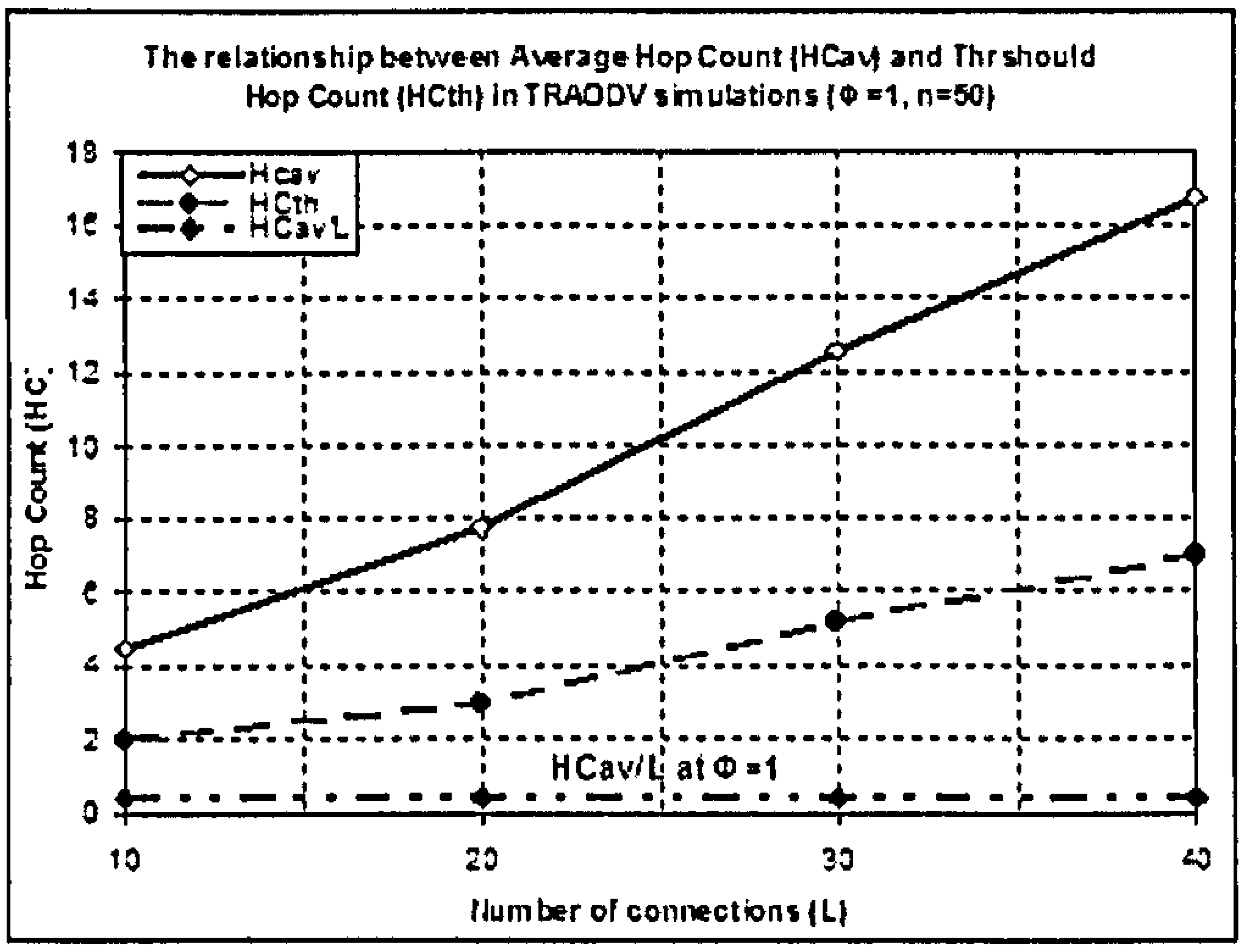

Figure 4.11: The relationship between HC_{av} and HC_{th} in TRAODV simulations (n=50)

Based on (4.2) and (4.3), we can find the rate of change (slope) of HC_{av} and HC_{th} respectively with respect to L. Hence, $\frac{dHC_{av}}{dL} = K$ is the rate of change of HC_{av} with respect to L, and $\frac{dHC_{th}}{dL} = \phi K^2$ is the rate of change of HC_{th} with respect to L. If ϕ=1 then, $\frac{dHC_{th}}{dL} = K^2$. As $K < 1$, the rate of change in HC_{th} with respect to L is much less than in HC_{th}, which is shown clearly in Figure 4.11.

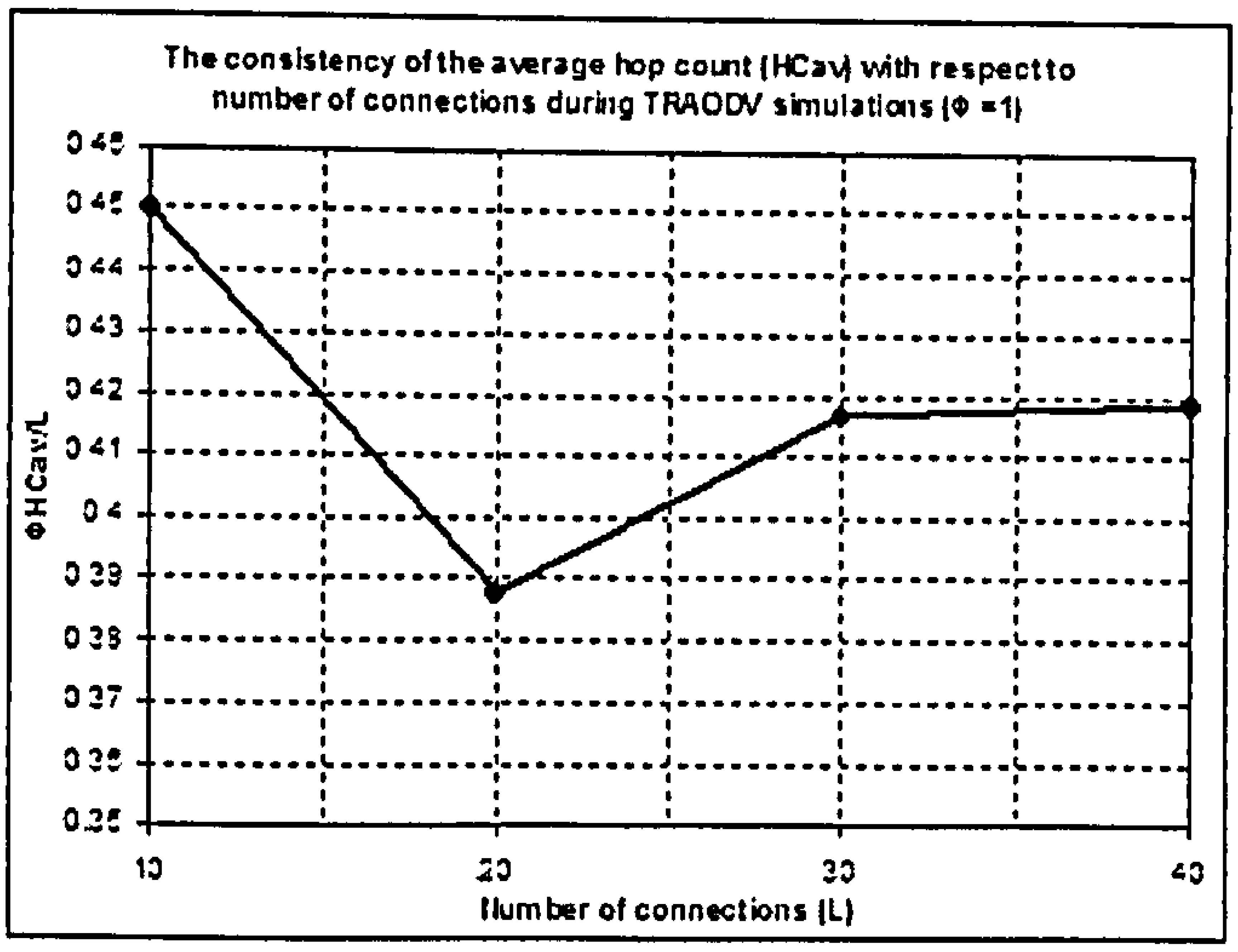

Figure 4.12: The consistency of HC_{av} with respect to L during TRAODV simulations ($\phi = 1$, n=50)

4.3.3 RMP mechanism in TRAODV

Route maintenance process in TRAODV and MRAODV are similar while it is different in AOMDV. In AOMDV, when the primary route fails, the backup route is used. If the backup route also fails, a new RDP is reinvoked by local repairing procedure between the source and the destination nodes to detect an alternative primary route and a single backup route. In TRAODV and MRAODV, if the primary route and all backup routes fail, a local RDP is invoked by local repairing procedure between the upstream node (at the first end of the broken link) and the destination node to detect an alternative primary route and multiple backup routes. If the local repairing also fails, the source node should re-establish a new global route discovery to detect a new set of multiple routes to the destination.

4.4 TRAODV Implementation and Simulation

The simulations are carried out using of NS2.26 under Linux platform of Fedora 5 to evaluate TRAODV against MRAODV, AOMDV, DSR, and TORA protocols. As mentioned earlier in Chapter 3, the implementation of AOMDV is modified for

MRAODV simulation by extending the RREP waiting time parameter to 20 seconds instead of 1 second in AOMDV simulations. Also, it is mentioned that the time of 20 seconds is measured by varying the waiting time until reaching the maximum number of multiple routes of a session between a source and destination nodes. In this case, the implementation of AOMDV which is involved by NS2.26 is applied to MRAODV with the required modifications, which means that MRAODV is simulated as a link-disjoint version of the original MRAODV due to the link-disjoint feature associated with the implementation of AOMDV protocol.

Another difference between MRAODV and AOMDV implementations is concerning scheduling process of multiple routes. For AOMDV, no multiple route scheduling is applied because it selects only one backup route (the next shortest path) for the primary one (the shortest path which has the least number of hops). Multiple route scheduling is implemented for MRAODV using Selective Weighted Round Robin (SWRR) algorithm which is developed and implemented in NS2 for AOMDV extensions by Gonner and Schatzmann [142]. SWRR algorithm is used in MRAODV by assigning a weight for each available route so that the weight is proportional to the number of hops of that route with respect to the number of connections. The weight and the next hop are stored in the routing table of the source node. The optimal selection of routes in MRAODV is accomplished based on the least weight of each route.

In TRAODV, two policies are applied to multiple routes selection in SWRR. The first policy is called N out of M in which best N is selected out of total M routes and the second policy is to use only the best ($N = 1$) out of M routes and keep the rest as backup [142]. The two selection policies mentioned above are used sequentially in TRAODV so that firstly N efficient routes are selected out of the total routes, and secondly the best route out of N is selected as the primary route and the rest out of N are kept as backup.

To apply these policies in TROADV, SWRP algorithm is utilised by assigning a weight for each available route so that the weight is proportional to number of hops of that route. However, the route that are concerned by TRAODV should have a hop number less than the average number of all hop numbers of all routes available for the same source node. In this case, the route is considered efficient; otherwise, the route is inefficient.

As shown in Figure 4.10, all routes in TRAODV are firstly stored in the routing table of the source node with their weights and the next hops. Then, the average number of hop counts of all routes in the table is estimated, and finally all inefficient routes are removed from the table. Hence, only the efficient routes are stored in the routing table. The optimal selection of routes in TRAODV is accomplished based on the least weight of each route.

Even though that MRAODV is a non-disjoint and TRAODV is a link-disjoint multipath protocol, both of them are simulated here as link-disjoint versions due to the link-disjoint feature associated with the implementation of AOMDV. Simulations using this feature for these two protocols do not affect on the simulation results because they are mainly compared while they are subjected to the same conditions and the same disjoint restrictions. Moreover, the feature of MRAODV which is mainly utilized in TRAODV implementation is related only to waiting time extending during RREP procedure. Thus, TRAODV can be considered as a link-disjoint extension to the non-disjoint MRAODV protocol.

Simulations are carried out under the same simulation environment, mobility and connection models, input parameters, and performance metrics used in the simulations of the experimental study carried out in Chapter 3.

4.5 General Discussion

TRAODV approach is the first new approach developed in this thesis as a link-disjoint multipath extension to AODV in MANETs. TRAODV aims to reduce routing packets overhead and average end-to-end delay overhead which are considered disadvantages in the existing extensions; AOMDV and MRAODV. TRAODV tries to improve the RDP of MRAODV by detecting the waiting time needed to receive threshold number of efficient routes. TRAODV also tries to increase the route efficiency in the routing table of a source node.

TRAODV is implemented and simulated using NS2 environment by modifying the implementation of MRAODV. While MRAODV extends the waiting time of RREP until receiving all possible routes by the source node including efficient and inefficient routes which is measured as 20 seconds, TRAODV calibrates the waiting time between 1 sec (AOMDV mode) and 20 sec (MRAODV mode) until receiving threshold number of efficient routes, which are only the routes that are stored in the routing table of the source node. Threshold waiting times of TRAODV are measured approximately at 5 sec, 8 sec, 12 sec, and 14 sec as the average times of all scenarios listed in Table 7.2. TRAODV performance is evaluated against the performances of MRAODV, AOMDV, DSR, and TORA protocols as shown later in the results study presented in Chapter 7. The environment of TRAODV simulations, input parameters are the same used in Chapter 3 for the simulations of traditional protocols and multipath extensions to AODV. Tables 7.1 and 7.2 in Chapter 7 show the fixed parameters and the different scenarios of the simulations of TRAODV. The main disadvantage of TRAODV is that it concerns only the phase of RDP, it does not concern the route maintenance process in AODV. As shown by simulation results, TRAODV performs well in terms of routing packets overhead, however it still performs worse than the traditional protocol TORA. Moreover, the performance of TRAODV is reduced in terms of average end-to-end delay compared to AOMDV and MRAODV. The second novel approach of this thesis, ORMAD, which is presented later in Chapter 5 focuses on the RMP of TRAODV aiming at reducing routing packets overhead and average end-to-end delay in multipath extensions to ADV protocol.

Chapter 5

On-demand Multiple Route Maintenance in AODV (ORMAD Approach)

5.1 Introduction

Many multipath extensions to AODV protocol in MANETs are conducted to solve the problem of the single path abstraction associated with the traditional AODV. However, few of these extensions to AODV focus on the two core processes of routing; RDP and RMP by applying the RMP to all routes that may be failed due to a broken link including efficient and inefficient routes. Applying RMP to inefficient routes leads to more alternatives of inefficient subroutes due to increasing in number of hops. In addition, routing overhead is increased and the network resources are consumed due to repairing inefficient routes. On the other hand, many literatures of multipath extensions to AODV deal with the route maintenance problem by invoking General RDP (GRDP) which sends an end-to-end RREQ from the source to the destination via intermediate node(s). Invoking GRDP frequently leads to increase routing overhead and consume the network resources such as bandwidth, energy, memory, and computing time.

This chapter presents our second novel approach of multipath AODV called On-demand Route maintenance in Multipath AODV (ORMAD) which applies RMP by invoking a Local RDP (LRDP) only for efficient routes starting with the most optimum route and ending with the least optimum route. ORMAD is a link-disjoint multipath extension to TRAODV which applies the concepts of threshold waiting time, threshold number of efficient routes, and threshold hop count to both phases; RDP and RMP. These concepts are defined earlier in Chapter 4. Thus, unlike TRAODV which focuses only on the RDP, ORMAD approach focuses on both phases; RDP and RMP. ORMAD applies RMP only to efficient routes which are selected in the RDP and when a route fails, it invokes a local repair procedure between upstream and downstream nodes of the broken link. This mechanism produces a set of alternative subroutes with less number of hops which enhances route efficiency and consequently minimises the routing overhead.

ORMAD aims to enhance the routing packets overhead and the average end-to-end delay overhead in multipath extensions to AODV protocol. It is implemented using NS2 and its performance is evaluated against the previous extensions to AODV; TRAODV, MRAODV and AOMDV, in addition to the two traditional multipath protocols; DSR and TORA. Results study and evaluation of ORMAD are presented later in Chapter 7.

5.2 Related Work of ORMAD

This section presents the related work of ORMAD which is almost related to the route maintenance process in multipath extensions to AODV. Three directions have been addressed in the literatures for manipulating route failures in reactive routing protocols of MANETs. The first direction is related to the single path protocols that launch a new GRDP when a link fails. The second direction is related to the multipath protocols. Similar to the first direction, they launch a GRDP when a link fails. The third direction is related to the multipath protocols that launch a LRDP - during a RMP - when a link fails and then, if the problem could not be fixed, they re-establish a new GRDP.

The first direction is the traditional direction which is adopted by the original single path protocols such as the original AODV. In this direction, when a link failure is detected in the single route maintained in the routing table of a source node, a new GRDP should be invoked to rediscover an alternative route. This process is achieved by flooding a network-wide RREQ packets via different paths to the same destination and waiting for RREP(s) that would be sent by the destination [12]. A single route (the optimal) is selected again among many detected routes and this new single route only can be used for data transmission as long as the route is valid [12].

In protocols of this direction, invoking frequent RDP leads to increase both delay and control overhead [92].

The second direction is adopted by many multipath extensions to on-demand protocols such as DSR and its early extensions such as [17], [91], [127] and [128], TORA and its extension, Routing On-demand Acyclic Multipath (ROAM) [129] and many other on-demand multipath extensions such as [105], [125], [130], [131] and [132]. In most of these multipath extensions, a concept of backup route(s) often used, when all available routes maintained in a multipath routing table of a source node are become invalid due to link failures, a new GRDP should be invoked to rediscover an alternative set of routes.

The third direction is adopted by the most recent multipath extensions to AODV protocol such as TRAODV, MRAODV [13], AODVM [89], NMH [124] and AODV-MM [126]. In these protocols, if all available routes fail, a LRDP should be invoked between the upstream node of the broken link and the destination node to detect an alternative set of routes. The main objective of all multipath extensions of this direction is to minimise frequent route re-discovery attempts and consequently minimising delay and control overhead. ORMAD belongs to this direction of multipath extensions in MANETs with a modification related to invoking a LRDP between upstream and downstream nodes instead of upstream and destination nodes.

5.3 RMP Mechanism in AODV extensions

In this subsection, the mechanism of RMP in AODV extensions is described covering three mechanisms of the three directions of route maintenance in AODV and its extensions. The first direction is related to RMP mechanism in the original single path AODV which is described in details before in Chapter 4. Thus, only RMP mechanisms of the other two directions are presented in this chapter.

5.3.1 RMP mechanism in the second direction of AODV extensions

Similar to RMP mechanism in the original single path AODV (the first direction), protocols of the second direction also uses route error (RERR) messages for route maintenance. As described for the original AODV, when a node detects a broken link to the next hop, it generates a RERR message that contains a list of unreachable destinations and sends it to related nodes.

The main difference between RMP mechanism in the first and the second directions is that when the primary route fails in the first direction, the source node should re-establish a new global route discovery directly to detect an alternative route to the same destination while in the second direction, the source node should first try to employ an alternative route from the set of routes that are maintained in its routing table since the most recent global route discovery is invoked. If all alternative multiple routes maintained in its routing table fail, the source node should re-establish a new global route discovery to detect a new set of multiple routes to the same destination. Figure 5.1 shows a conceptual activity diagram for RMP procedure during a procedure of sending a data message in the second direction protocols of multipath AODV extensions.

5.3.2 RMP mechanism in the third direction of AODV extensions

Similar to RMP mechanism in the second direction, protocols of the third direction also uses route error (RERR) messages for route maintenance. As described above for the second directions, when a node detects a broken link to the next hop, it generates a RERR message that contains a list of unreachable destinations and sends it to related nodes.

The main difference between RMP mechanism in the second direction and that in the third direction is that when the primary route fails in the second direction, the source node should try to utilise all available multiple routes maintained in its

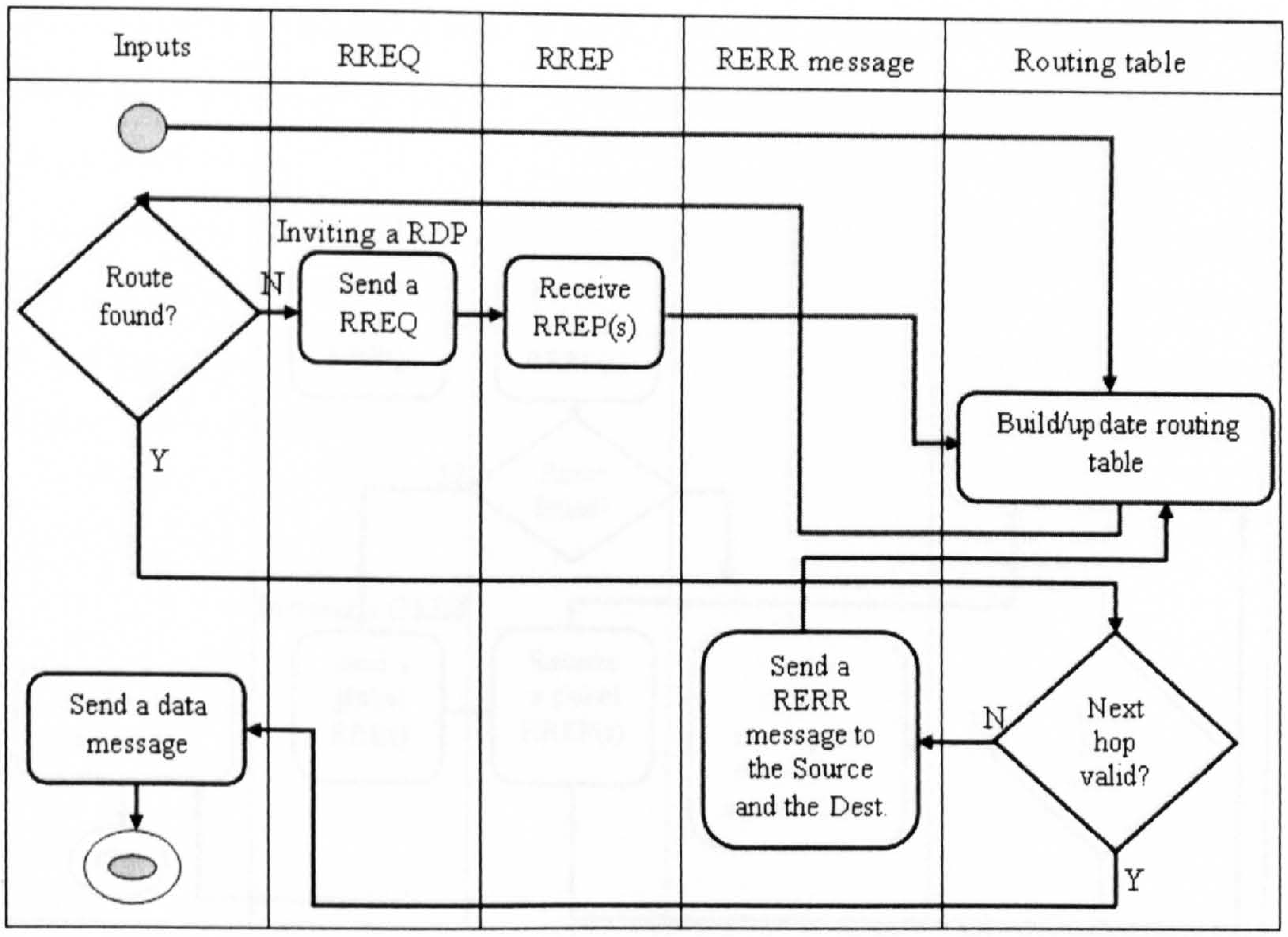

Figure 5.1: RMP in the second direction protocols

routing table before re-establishing a new global route discovery to detect a new set of multiple routes. In the third direction, when the primary route fails, the source node should try multiple routes and if all of them fail, it should try a local repairing by invoking a local route discovery between the upstream node of the broken link and the destination node. And finally, if the local repairing also fails, the source node should re-establish a new global route discovery to detect a new set of multiple routes to the destination. Figure 5.2 shows a RMP in of the third direction protocols of multipath AODV extensions with the restrictions of the waiting time and threshold number of routes.

5.4 RMP Mechanism in ORMAD Approach

As mentioned earlier in the previous section, ORMAD belongs to the third direction of routing maintenance in multipath AODV. As shown in Figure 5.3, ORMAD

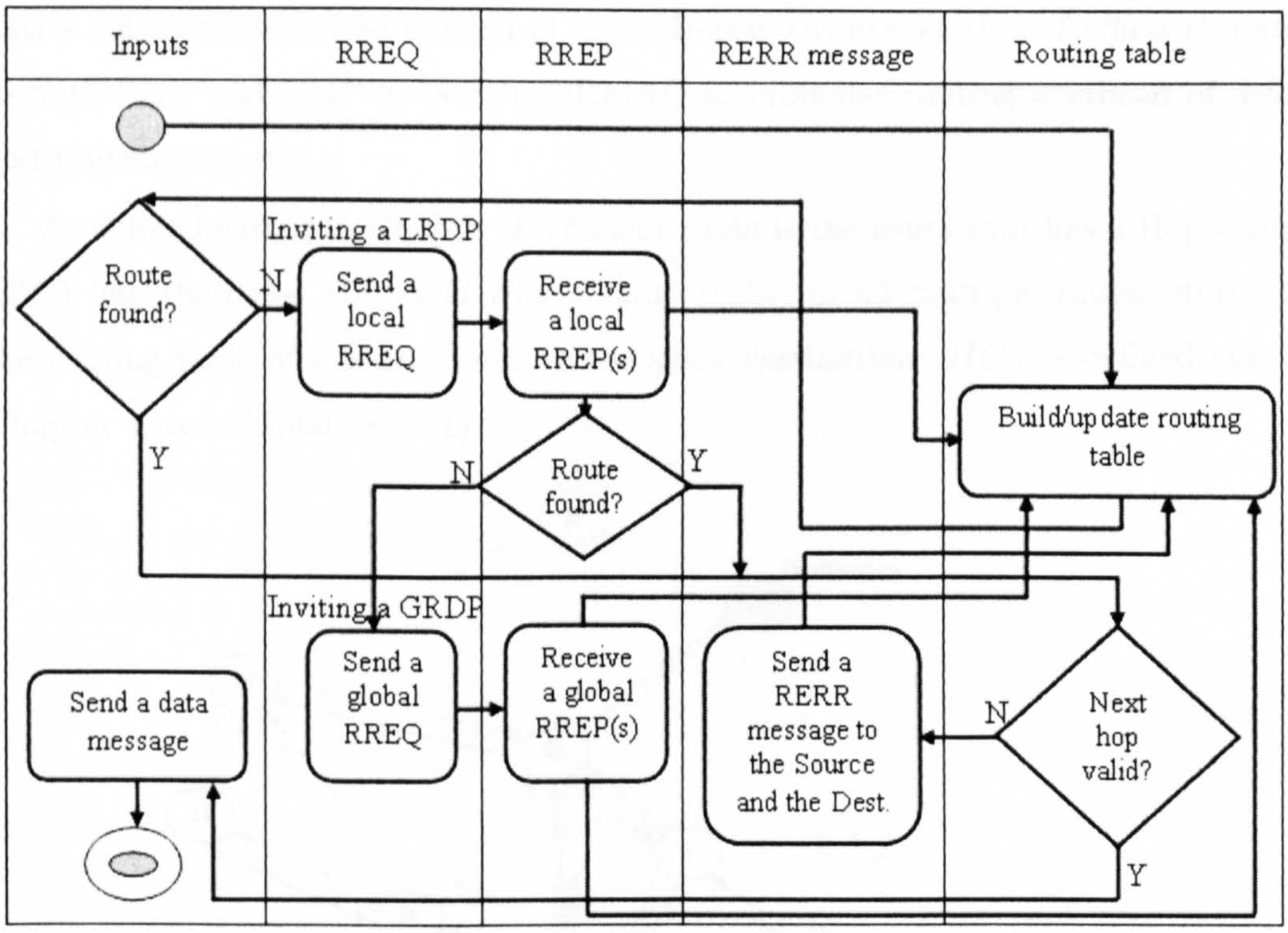

Figure 5.2: RMP mechanism in the third direction protocols

utilises the idea of LRDP between any two neighbours upstream and down stream nodes [13] of a broken link while the other extensions of the third direction invoke a LRDP between the upstream node and the destination. The idea of LRDP is addressed in some multipath routing approaches such as [13], [124], [136], and [137]. In such approaches, it is supposed that when a link fails, the intermediate nodes are responsible to rediscover other alternative routes using their routing tables. However, in such multipath extensions, a RMP can be applied to any failed route regardless of its efficiency. Hence, an inefficient route can be get repaired regardless of generating more inefficient alternative routes as a result of applying a RMP to an inefficient broken route. To avoid such redundancy in the number of inefficient routes, ORMAD applies RMP only to efficient routes which are selected in the route discovery phase. It also invokes the local repairing procedure only between the upstream and the downstream nodes which leads to minimise routing overhead and produce alternative subroutes with less number of hops. Hence, the abstraction of *efficient routes* in both RDP and RMP is used in ORMAD to minimise routing overhead of delay and routing packets.

As defined earlier in Chapter 4, efficient route is the route that has a Hop Count (HC) less than the *Threshold Hop Count* (HC_{th}) of all multiple routes stored in the routing table of a source node to the same destination. HC_{th} is defined also in Chapter 4 as in Equation (4.1).

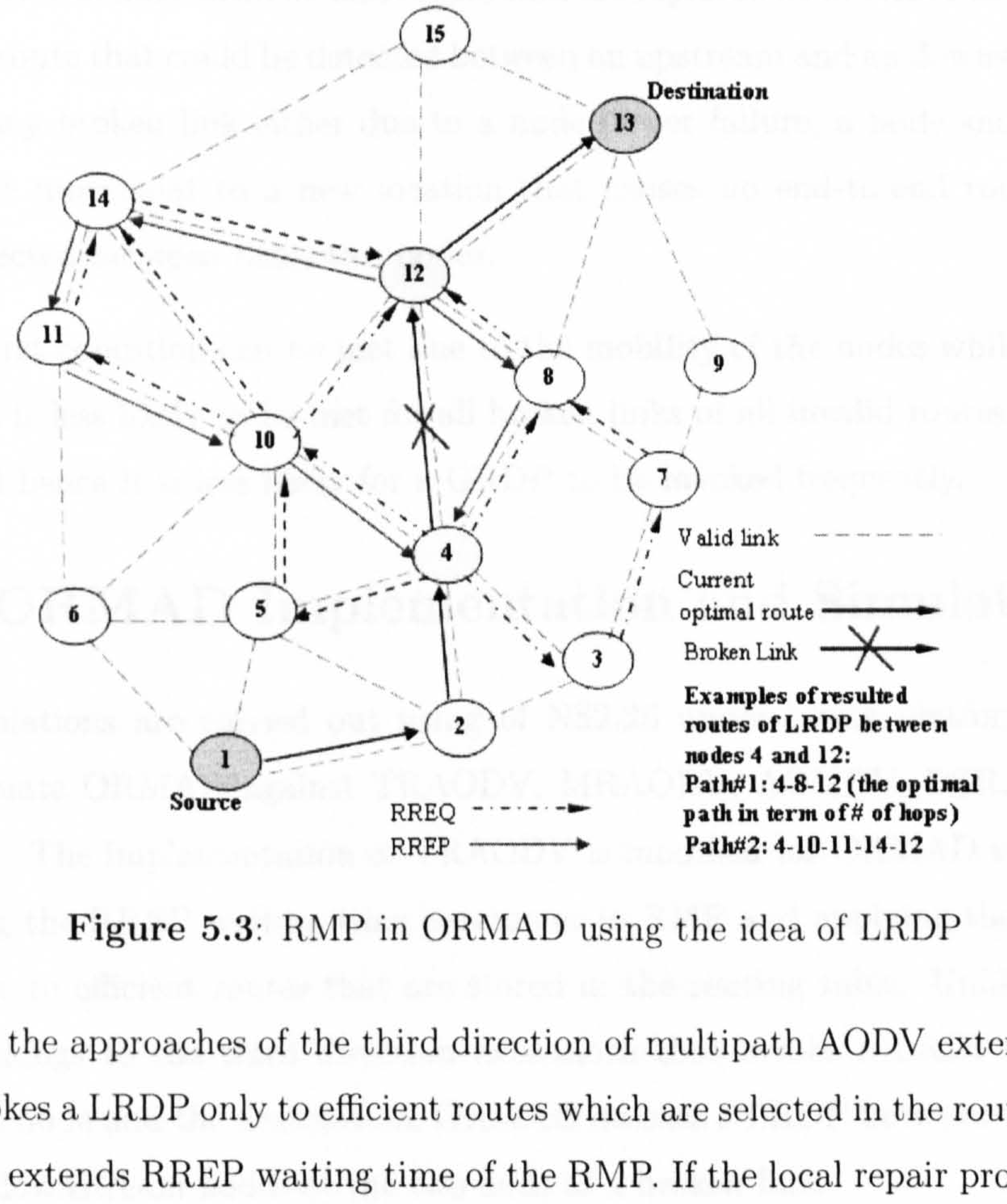

Figure 5.3: RMP in ORMAD using the idea of LRDP

Unlike the approaches of the third direction of multipath AODV extensions, ORMAD invokes a LRDP only to efficient routes which are selected in the route discovery phase and extends RREP waiting time of the RMP. If the local repair procedure fails to fix the problem, a new GRDP is invoked. This mechanism leads to minimise routing overhead of both delay and network resources consuming by minimising the attempts of route re-discovery. Invoking a new GRDP is very less likely to be occurred in ORMAD because it should match many conditions. Some of these conditions have a less probability to be met for all invalid routes and all broken links at the same time. For example, the following are some conditions required to be met to invoke a new GRDP:

1. All routes in the routing table fail including both efficient and inefficient routes meaning that a valid inefficient route can be used if all efficient routes became invalid which is rarely occurred.

2. All broken links in all invalid routes that are repaired do not have any alternative subroute that could be detected between an upstream and an downstream nodes of any broken link either due to a node power failure, a node shutdown, or a node movement to a new location that causes no end-to-end route could be detected between these two nodes.

The first condition can be met due to the mobility of the nodes while the second condition is less likely to be met for all broken links of all invalid routes at the same time, and hence it is less likely for a GRDP to be invoked frequently.

5.5 ORMAD Implementation and Simulation

The simulations are carried out using of NS2.26 under Linux platform of Fedora 5 to evaluate ORMAD against TRAODV, MRAODV, AOMDV, DSR, and TORA protocols. The implementation of TRAODV is modified for ORMAD simulation by extending the RREP waiting time parameter in RMP and applying the local repair procedure to efficient routes that are stored in the routing table. Unlike TRAODV which belongs to the third direction extensions that invoke a LRDP between the upstream node and the destination, ORMAD invokes a LRDP between the upstream and the downstream nodes at the two ends of a broken link.

The selection strategy and scheduling process of multipath routing that is used in TRAODV is also used for ORMAD. SWRR algorithm is used for TRAODV by assigning a weight for each available route so that the weight is proportional to the number of hops of that route with respect to the number of connections. The weight and the next hop are stored in the routing table of the source node. The optimal selection of routes in ORMAD is accomplished based on the least weight of each route. Also the concept of threshold hop count is also used in ORMAD to determine whether the route is efficient or not. This concept is applied to both phased RDP and RMP. In RDP the concept of threshold hop count is applied to the hop count of the route, while it is applied in RMP to the hop count of the subroute that may be detected by local repairing between the upstream and the down stream nodes at the two ends of a broken link.

Simulations are carried out under the same simulation environment, mobility and connection models, input parameters, and performance metrics used in the simulations of the experimental study carried out in Chapter 3 and the same as the environment of TRAODV simulations.

5.6 General Discussion

ORMAD approach is the second new approach developed in this thesis as a link-disjoint multipath extension to TRAODV in MANETs. ORMAD aims to reduce routing packets overhead and average end-to-end delay overhead which are considered disadvantages of the previous extensions; TRAODV, MRAODV and AOMDV. ORMAD tries to improve the performance of multipath extensions to AODV by applying the concepts of threshold waiting time and threshold number of efficient routes to both phases RDP and RMP. Figures 5.2 and 5.3 show the mechanism of the RMP in ORMAD approach which is similar to RMP mechanism of the third direction protocols of multipath AODV extensions with the restrictions of the waiting time and threshold number of routes. ORMAD invokes a LRDP only for efficient routes with extending RREPs waiting time of the RMP, and if this process fails to fix the problem, a new GRDP is invoked. This mechanism leads to minimise routing overhead including routing packet overhead, average end-to-end delay, and even network resources consuming by minimising the attempts of route rediscovery.

ORMAD is implemented and simulated using NS2 environment by modifying the implementation of TRAODV. While TRAODV applies the concepts of threshold waiting time and threshold number of efficient routes to RDP phase, ORMAD applies them to both phases RDP and RMP. The boundaries of RDP waiting time that are used in ORMAD are similar to that used in TRAODV which are between 1 sec (AOMDV mode) and 20 sec (MRAODV mode). However, the boundaries of RMP waiting time used in ORMAD are between 1 and 5 seconds. Justifications of using these boundaries are explained later in Chapter 7.

Threshold waiting times of RMP is measured approximately at 3 sec as the average time of all scenarios listed in Table 7.2. As shown by simulation results of ORMAD, varying both waiting times of RDP and RMP in different scenarios affects the performance of ORMAD in terms of all performance metrics. ORMAD performance is evaluated against the performances of TRAODV, AOMDV, MRAODV, DSR, and TORA protocols as shown later in the results study presented in Chapter 7. The environment of ORMAD simulations, input parameters are the same used in Chapter 3 for the simulations of traditional protocols and multipath extensions to AODV and the same as TRAODV simulations. Tables 7.1 and 7.2 in Chapter 7 show the fixed parameters and the different scenarios of the simulations of ORMAD. As shown by simulation results, ORMAD performs well in terms of routing packets overhead which is the closest to TORA performance, however it still less than the performance of the traditional protocol TORA. Moreover, the performance of ORMAD in terms of average end-to-end delay is enhanced ORMAD compared to TRAODV, MRAODV, and AOMDV, especially in high mobility scenarios.

Relevant concepts are formalised for ORMAD approach and conducted in Chapter 6 as an analytical model in this thesis involving the whole process of multipath routing in AODV extensions. ORMAD analytical model describes how the two phases RDP and RMP interact with each other with regard to two performance metrics; total number of detected routes and route efficiency.

Chapter 6

Formalising Relevant Concepts for ORMAD Approach

6.1 Introduction

Multipath routing modelling in MANETs is not addressed sufficiently compared to the increasing significance of multipath routing in so many applications of MANETs. For example, very few literatures are interested in developing a model for the whole process of multipath extensions to AODV with an analytical description of the two main phases of AODV extensions; RDP and RMP and how they interact with each other. Additionally, very few literatures are interested in developing an analytical model that studies the impact of RREP timeout on the total number of detected routes and the route efficiency in both phases RDP and RMP. Also, a researcher cannot find easily an analytical model that describes the relationship between the behaviours of RREP timeouts in these two phases and how they interact with each other.

Furthermore, efficient routes and route efficiency are new expressions focused recently in multipath routing area. Unfortunately, these expressions are not addressed precisely in the most literatures of multipath routing. A difficulty is encountered to find out a precise definition for route efficiency either in traditional routing protocols or their extensions in MANETs. These two expressions become significant in the modelling of RMP in multipath routing. Additionally, most literatures of multipath extensions to AODV deal with the route maintenance problem by invoking GRDP which sends an end-to-end RREQ from a source to destination via intermediate node(s). Invoking GRDP frequently leads to increase routing overhead and a higher consumption of the network resources such as bandwidth, energy, memory, and computing time.

6.1 Introduction

Some multipath analysis approaches are conducted in some literatures such as [92], [103], and [133]. NDMR [92] is a recent extension of AODV. It utilises from the path accumulation feature of DSR for AODV so that it can discover multiple node-disjoint routing paths with a low routing overhead. In [133] and its extension [134], a routing scheme that uses multiple paths simultaneously is proposed. The information is divided between multiple paths hopefully the information would be received at the minimum delay. However, it does not concern the whole process of multipath extensions. In [103], an analysis of non-disjoint multipath routing is introduced by estimating the probability of path disjointness. However, the approach does not concern the whole process of multipath extensions. Instead, it concerns only the disjointness problem in on-demand extensions. Although they are good frameworks for on-demand protocols, the approaches [92], [103], [133], and [134] do not take into account the effects of mobility, connectivity and waiting time on route efficiency and the total number of multiple routes in on-demand extensions.

This chapter introduces an analytical model for the whole process of ORMAD approach as one of the most recent extensions to AODV developed in this thesis. The analytical model describes the two main core phases of ORMAD; RDP and RMP and how these two phases interact with each other with regard to the total number of detected routes and the route efficiency. Based on this model, ORMAD is analysed, implemented using Matlab 6.0, tested, and evaluated against multipath extensions to AODV of the third direction using two performance metrics; total number of routes and route efficiency. Also, route efficiency that is achieved by ORMAD is evaluated against the other multipath AODV extensions of the third direction. The testing and evaluation results are presented later in Chapter 7 to prove the behaviour of the total number of multiple routes and the route efficiency in terms of different scenarios of connectivity, mobility, and route reply waiting time.

6.2 General analysis of ORMAD Approach

Let us suppose that N is a number of nodes, L is a number of initial links, and B is a number of broken links in a particular session. L is chosen based on (6.1) and B is chosen based on (6.2).

$$L = \alpha N, \quad \frac{N}{2} \leq \alpha \leq \frac{N(N-1)}{2} \tag{6.1}$$

$$B = \beta L, \quad 0 \leq \beta \leq 1 \tag{6.2}$$

6.2.1 Connectivity ratio (η)

From (6.1), the term $\frac{N}{2} \leq \alpha \leq \frac{N(N-1)}{2}$ is normalised to become as in (6.3):

$$\frac{1}{N-1} \leq \frac{2\alpha}{N(N-1)} \leq 1 \tag{6.3}$$

Let us define $\frac{2\alpha}{N(N-1)} = \eta$, where η is the *Connectivity Ratio, CNR* which indicates the ratio of links in the network with respect to the total number of nodes N. *Connectivity* is used recently in many literatures related to MANETs in different ways and different definitions. For example, connectivity is defined in [138] as the fraction of time that every node is reachable (in one or more hops) by every other node. While the definition of connectivity in [138] concerns the time fraction of a connection, the connectivity ratio definition in this research concerns the ratio of number of links with respect to number of nodes in a network. From (6.3), the boundaries of η can be written as in (6.4):

$$\frac{1}{N-1} \leq \eta \leq 1 \tag{6.4}$$

6.2.2 Mobility ratio (μ)

By substituting L from (6.1) into (6.2), number of broken links can be rewritten as in (6.5):

$$B = \alpha\beta N, \quad 0 \leq \alpha\beta \leq \frac{N(N-1)}{2} \tag{6.5}$$

From (6.5), the boundaries of $\alpha\beta$ are normalised to become as in (6.6):

$$0 \leq \frac{2\alpha\beta}{N(N-1)} \leq 1 \tag{6.6}$$

Let us define $\frac{2\alpha\beta}{N(N-1)} = \mu$, where μ is the *Mobility Ratio, MBR* which indicates the ratio of broken links with respect to the number of nodes due to mobility in a network. From (6.6), the boundaries of μ can be written as in (6.7):

$$0 \leq \mu \leq 1 \tag{6.7}$$

6.2.3 Waiting time ratios (T_o, T_m)

Let us define T_o, represents a GWT, as the initial waiting time ratio which is used in the last GRDP and T_m, represents a LWT, as the *Waiting Time Ratio, WTR* which is used in the last RMP. T_o and T_m boundaries can be written as in (6.8):

$$\tau_o \leq T_o \leq 1, \quad \tau_o \leq T_m \leq 1 \tag{6.8}$$

If $T_o = \tau_o$ (the mechanism of AODV and its early extensions), a very small waiting time, τ_o, is applied to RREP packets for a RDP. And, if $T_o = 1$ (MRAODV mechanism), meaning that the waiting time needed to receive all possible RREP packets is applied until no more RREP packets are available. Waiting time of the most recent multipath extensions is often between τ_o and 1. T_m does not seem to be used as a variable in most of literatures that are revised during this research. Very few literatures has argued this issue briefly, for example, a tuneable timeout value is used in [139] during a local repair process of a failed route. If the route is not repaired within the timeout, it should be invalidated. However, [139] concerns only the repairing of a single path which is replaced by another single path. It does not introduce a multipath scheme nor analyze the timeout value and its relationship with the timeout of the RDP.

6.3 The total number of multiple routes (M_t)

Suppose that the terms $\frac{\eta T_o}{\mu}$ and $\frac{\eta T_m}{\mu}$ are denoted by λ_o and λ_m respectively as shown in (6.9), λ is defined generally in this chapter as the MDG of a multipath protocol.

$$\lambda_o = \frac{\eta T_o}{\mu}, \quad \lambda_m = \frac{\eta T_m}{\mu} \tag{6.9}$$

6.3.1 M_t after applying a RDP

Suppose that M_o is the maximum number of routes that could be received due to a GRDP of a source node during a particular session in ideal circumstances (an ideal circumstance can be offered at the highest λ_o, which means the highest connectivity, the lowest mobility, the longest waiting time T_o, see Equation (6.9)). M_t, the total number of routes in a routing table of a source node per session is proportional to the maximum number of routes M_o, and thus the initial M_t can be written as in (10):

$$M_t = C_o \lambda_o M_o \tag{6.10}$$

Where C_o is the multipath constant of a RDP.

Assumptions:

It is assumed in this analytical study that M_o is the maximum value that could be reached in the ideal circumstances. In the conventional wisdom of MANETs, the higher the connectivity, the higher the probability of a route reply. The higher the mobility the higher the probability of a route reply and a link to be broken down. The longer the waiting time the higher the probability of a route reply and a link to be broken down. Assumptions here come from this wisdom, and thus this study tries to know how the behaviour of M_t would be affected by the variability of mobility, connectivity and waiting time ratios and how M_t converges or diverges from the maximum value (M_o) of the ideal case due to the variability of these ratios.

An efficient route can be easily detected by verifying the route efficiency bit (*e-bit)* in the routing table as shown in Table 6.1 which shows the routing table structure in the analytical model of ORMAD . If e=1, the route associated with the bit is efficient otherwise, the route is inefficient. When a LRDP finishes and the alternative subroutes are detected, old contents of the routing table shown in Table 6.1 should be flushed and then updated. Prior to flushing the table, some estimated information that may be needed in the future should be saved, such as M_t, M_o, M_{eo}, M_{no}, H_{oav}, B_r and H_o (defined later in this chapter). Routing table contents is updated by the information of the alternative routes detected by applying the *Combinations* function *(nCr)* between the links that are still valid in a particular invalid main route and all subroutes detected due to the LRDP applied to each link in the primary route. New routes are combined now according to the sequence of the still-valid-links and the subroutes detected for each broken link in the primary route. The parameters related to the RMP can be estimated now, such as M_t (updated), M_m, M_{em}, M_{nm}, H_{mav}, and route efficiency bit (e).

Note:

In this chapter, when the "route" is mentioned in a routing table, it means the next hop of that route in the routing table as shown in Table 6.1).

Table 6.1: Routing table structure in ORMAD

SrcID	DesID	# of Hops	Next Hop	RREQ#	neighbours	Efficient (e)
Integer	Integer	Integer	Integer	Integer	String	Yes/No

6.3.2 M_t after applying a RMP

Suppose that M_m is the maximum number of routes that are generated due to a RMP in the ideal circumstances (same assumptions as for M_o except the longest waiting time here is T_m). Suppose that M_{eo} is a number of efficient routes that are found in a routing table before applying the RMP and suppose that all these efficient routes can fail due to link failures. M_{eo} is defined as a number of efficient routes that became invalid routes due to link failures. These efficient routes would be replaced by other valid routes in a routing table during RMP. Suppose that M_{em} is a number of efficient routes that are detected due to a RMP and M_n is the total number of inefficient routes that are detected during the two processes, RDP and RMP. And finally, suppose that M_{no} and M_{nm} are numbers of inefficient routes that are detected due to RDP and RMP respectively.

6.3.3 Multiple-route scenarios

M_o and M_m and then M_t can be affected by connectivity, mobility and waiting time factors as follows:

- M_o increases when connectivity ratio increases, that is due to increasing in the number of links.
- M_o decreases when mobility ratio increases, that is due to increasing in the number of link failures.
- M_m increases when mobility ratio increases, that is, increasing in mobility ratio may cause more link failures which lead to a need for inviting more RMPs and then more alternative routes could be detected.
- M_m increases when connectivity ratio increases, that is, in high connectivity scenarios, a RMP has a chance to detect more subroutes between upstream and downstream nodes. Also, when a connectivity ratio increases, larger number of inefficient routes (M_{nm}) with larger hop count could be detected during a RMP.
- Both M_o and M_m increase when waiting time ratio increases, that is, more RREPs could be received by a source node in the two processes, RDP and RMP.
- And finally, M_t generally decreases when mobility ratio increases, that is, increasing in mobility ratio causes more link failures in the efficient routes (M_{eo}) which are replaced and then removed from a routing table during RMP(s).

Based on these scenarios and since M_t is proportional to M_o and M_m (M_o is considered here the initial number of routes in a routing table before applying a RMP) and since the number of invalid efficient routes (M_{eo}) is replaced by a valid number of alternative routes that are involved by M_m, therefore, M_t for all multipath

AODV extensions except ORMAD can be rewritten as in (6.11):

$$M_t = C_o \lambda_o (M_o - M_{eo}) + C_m \lambda_m M_m \tag{6.11}$$

Or it can be expressed in terms of η, μ, T_o and T_m as in (6.12):

$$M_t = C_o \tfrac{\eta T_o}{\mu} (M_o - M_{eo}) + C_m \tfrac{\eta T_m}{\mu} M_m \tag{6.12}$$

Where C_m is the multipath constant of a RMP.

6.4 Number of maintenance routes (M_m)

Consider H_{mav} the average hop count detected after updating a routing table during a RMP, H_{oi} the initial hop count of a particular effective route i, B_{ri} a number of broken links in route i and T_m the waiting time ratio of LRDP between upstream node and downstream node of a particular broken link in route i during a LRDP of a particular session. Suppose that H is a hop count of subroutes detected due to a RMP of a particular broken link j and waiting time ratio T_m. H increases when receiving more subroutes due to a waiting time extension (T_m) of a LRDP and thus H increases when T_m increases and consequently, M_m increases. M_m also increases when connectivity ratio and mobility ratio increase. H_i, the total hop count of all subroutes that are detected due to all LRDPs of all broken links in a particular primary route i can be written as in (6.13):

$$H_i = \sum_{j=1}^{B_{ri}} \sum_{k=1}^{R_{ij}} H_{ijk} \tag{6.13}$$

Where H_{ijk} is a hop count of a particular subroute k detected as an alternative subroute for a particular broken link j in a particular primary route i that became invalid in a routing table of a source node, R_{ij} is the total number of subroutes detected as alternatives for a particular broken link j in a particular primary route i that became invalid in a routing table of a source node and finally, B_{ri} is the total number of broken links in a particular primary route i that became invalid in a routing table of a source node. Suppose that L_{vi} is a number of valid links in a primary route i, it can be written as in (6.14):

$$L_{vi} = (H_{oi} - B_{ri}) \tag{6.14}$$

Where H_{oi} is the initial hop count of a particular primary route i that became invalid in a routing table of a source node. The term $(H_{oi} - B_{ri})$ is the difference between a hop count of a particular route i and the number of broken links in that route, the result is the number of the valid links in the primary route i.

M_{mi}, the total number of subroutes that can be detected due to a RMP applied to all broken links in a particular invalid primary route i can be written as in (6.15) using *combinations* function:

$$M_{mi} = \frac{L_{vi}!}{H_i!\,(L_{vi} - H_i)!} \tag{6.15}$$

Combinations function is applied to L_{vi} and H_i to obtain all alternative routes of an invalid primary route i. M_m, the total number of multiple routes detected in a routing table of a source node in a particular session due to a RMP, can be written as in (6.16):

$$M_m = \sum_{i=1}^{M_{eo}} M_{mi}$$

$$M_m = \sum_{i=1}^{M_{eo}} \frac{L_{vi}!}{H_i!\,(L_{vi} - H_i)!} \tag{6.16}$$

Where M_{eo} is the initial number of efficient routes that are currently repaired by a RMP. M_{eo} can be estimated by increment a counter H_{eo} for each detected route during a GRDP. A route is considered efficient if it has a hop count less than HC_{th} which is estimated by Equation (4.1) in Chapter 4. As shown by Equation (4.1), HC_{th} is estimated based on H_{oav}, the average hop count of all initial routes (M_o) in a routing table, and the number of connections L. H_{oav} can be derived as in (6.17).

After applying (6.17), let $M_{eo} = H_{eo}$.

$$H_{oav} = \frac{1}{M_o} \sum_{i=1}^{M_o} H_{oi} \tag{6.17}$$

By substituting H_i from (6.13) into (6.16), M_m can be rewritten as in (6.18):

$$M_m = \sum_{i=1}^{M_{eo}} \frac{L_{vi}!}{\left(\sum_{j=1}^{B_{ri}} \sum_{k=1}^{R_{ij}} H_{ijk} \right)! \left| L_{vi} - \sum_{j=1}^{B_{ri}} \sum_{k=1}^{R_{ij}} H_{ijk} \right|!} \tag{6.18}$$

Where the condition of M_m validity can be written as:

$$L_{vi} > H_i$$

Referring to (6.14), the condition of M_m validity can be also expressed in terms of H_{oi} and B_{ri} as in (6.19):

$$H_{oi} - B_{ri} > \quad H_i \tag{6.19}$$

The validity condition in (6.19) means that the total number of hops in all detected subroutes during a RMP of B_{ri} broken links in a particular primary route i must be less than the number of valid links in that route. From this condition, it is concluded that a waiting time T_m should not be so long. The longer the waiting time the larger the hop count of a detected subroute which leads to invalid number of M_m. This conclusion meets the assumption mentioned before in this section regarding the relationship between a route efficiency and a hop count, the larger the hop count the larger the number of inefficient routes. To maintain the positive result of (6.19) mathematically, modulus signs are used before applying the factorials.

M_t can be expressed in terms of hop counts by substituting M_m from (6.18) into (6.11), M_t can be rewritten as in (6.20):

$$M_t = C_o \lambda_o M_{to} + C_m \lambda_m M_m \tag{6.20}$$

Where:

$$M_{to} = (M_o - M_{eo})$$

And:

$$M_m = \sum_{i=1}^{M_{eo}} \frac{L_{vi}!}{\left(\sum_{j=1}^{B_{ri}} \sum_{k=1}^{R_{ij}} H_{ijk}\right)! \left| L_{vi} - \sum_{j=1}^{B_{ri}} \sum_{k=1}^{R_{ij}} H_{ijk} \right|!}$$

6.5 Number of efficient and inefficient routes

The *Optimal Route* is defined generally in a single path AODV extension as the route that has a minimum number of accumulative weight (number of hops or the accumulative delay between links involved by the path) [7]. In this chapter, the *Optimal Route* is defined here as the route that has a hop count less than the average hop count of all primary routes stored in a routing table including efficient and inefficient routes. From (6.20), the term M_{to} can be defined so that it is equal to $C_o\lambda_o(M_o - M_{eo})$ as a number of inefficient routes M_{no} detected in a routing table before applying a RMP. It can be expressed as in (6.21):

$$M_{no} = C_o\lambda_o(M_o - M_{eo}) \tag{6.21}$$

Since the total number of inefficient routes M_n is equal to the summation of the numbers of inefficient routes in the initial state - before applying a RMP - (M_{no}) and in the final state (M_{nm}) - after applying a RMP - , therefore, M_n can be written as in (6.22):

$$M_n = M_{no} + M_{nm} \tag{6.22}$$

M_{nm} can be estimated by increment a counter H_{nm} for each route detected in a LRDP. As define in this chapter, a route is considered efficient if it has a hop count greater than HC_{th} which is estimated here for subroutes detected by the RMP as shown in Equation (4.1) in Chapter 4. HC_{th} is estimated here based on H_{mav}, the average hop count of all routes (M_m) detected during a RMP in a routing table, and number of connections L. H_{mav} is derived as in (6.23). After applying (6.23), let $M_{nm} = H_{nm}$.

$$H_{mav} = \frac{1}{M_m} \sum_{i=1}^{M_m} \sum_{j=1}^{B_{ri}} \sum_{k=1}^{R_{ij}} H_{ijk} \tag{6.23}$$

Since it is obvious that $M_{nm} = M_m - M_{em}$, and from (6.21) and (6.22), M_n can be rewritten as in (6.24):

$$M_n = C_o\lambda_o\left(M_o - M_{eo}\right) + C_m\lambda_m\left(M_m - M_{em}\right) \tag{6.24}$$

Equation (6.24) can be also expressed in terms of η, μ, T_o and T_m as in (6.25):

$$M_n = C_o\frac{\eta T_o}{\mu}\left(M_o - M_{eo}\right) + C_m\frac{\eta T_m}{\mu}\left(M_m - M_{em}\right) \tag{6.25}$$

6.6 Route efficiency (E) of multipath AODV

Route efficiency E in multipath AODV can be generally derived as in (6.26):

$$E = \frac{M_t - M_n}{M_t} \tag{6.26}$$

From (6.11) and (6.25), E can be written as in (6.27) for all multipath AODV extensions except ORMAD:

$$E_{Other\_extensions} = \frac{C_m\lambda_m M_{em}}{C_o\lambda_o(M_o - M_{eo}) + C_m\lambda_m M_m}$$

$$E_{Other\_extensions} = \frac{M_{em}}{\frac{C_e}{T_e}\left(M_o - M_{eo}\right) + M_m} \tag{6.27}$$

Where C_e is the constant of route efficiency, $C_e = \frac{C_o}{C_m}$ and T_e is the waiting time factor of route efficiency, $T_e = \frac{T_m}{T_o}$, $T_m \leq T_o$. If $T_e = 1$, then $T_m = T_o$ which means that GRDP and LRDP should wait for RREPs using the same waiting time.

From (6.12), (6.25) and (6.27), it is concluded that M_t and M_n can be affected by η, μ, T_o and T_m while E is affected only by T_e. E increases when T_e increases (the best value when T_m becomes much closer than T_o regardless of the value of each one of them) while M_t and M_n increase when T_o or T_m or both of them increase. E is also affected by M_{eo} and M_{em} which depend on H_{oav} (see Equation (6.17)) and H_{mav} (see Equation (6.23)) respectively.

6.7 ORMAD analysis

In *ORMAD*, flushing routing table before applying RMP removes the term of M_{to} in (6.20) thus, M_t becomes as in (6.28):

$$M_t = C_m \lambda_m M_m \tag{6.28}$$

Equation (6.28) can be also expressed in terms of η, μ, T_o and T_m as in (6.29):

$$M_t = C_m \frac{\eta T_m}{\mu} M_m \tag{6.29}$$

For ORMAD, M_n can be written as in (6.30):

$$M_n = C_m \lambda_m (M_m - M_{em}) \tag{6.30}$$

Equation (6.30) can be also expressed in terms of η, μ, T_o and T_m as in (6.31):

$$M_n = C_m \frac{\eta T_m}{\mu} (M_m - M_{em}) \tag{6.31}$$

By substituting (6.28) and (6.30) into (6.26), E can be rewritten for ORMAD extension as in (6.32):

$$E_{ORMAD} = \frac{C_m \lambda_m M_m - C_m \lambda_m (M_m - M_{em})}{C_m \lambda_m M_m}$$

$$E_{ORMAD} = \frac{M_{em}}{M_m} \tag{6.32}$$

Route efficiency ratio that is achieved by other multipath AODV extensions with respect to ORMAD can be obtained by dividing (6.27) on (6.32) as shown in (6.33):

$$E_{ratio} = \frac{E_{Other\_extensions}}{E_{ORMAD}} = \frac{M_m}{\frac{Ce}{Te}(M_o - M_{eo}) + M_m}$$

$$E_{ratio} = \frac{1}{\frac{C_e}{T_e}\left(\frac{M_o - M_{eo}}{M_m}\right) + 1} \tag{6.33}$$

From (6.20), it can be concluded the following:

- M_t, can be affected by η, μ, T_o , T_m and M_{eo}.

- The result of the term $C_o\frac{\eta T_o}{\mu}(M_o - M_{eo})$ does not lead to any efficient route and thus all routes detected by applying this term could be considered inefficient routes.

By comparing (6.11) with (6.28), ORMAD may lead to less number of total routes (M_t). However, it minimises the number of insufficient routes (M_n), and thus route efficiency should be essentially tested before issuing a judgment regarding a satisfaction of the total number of routes. Also, from (6.33), it can be concluded that the route efficiency ratio is always <1 and in the worst case it is equal to 1 (in case of $M_o = M_{eo}$). Thus, it is clear that ORMAD outperforms other multipath extensions in terms of maximising route efficiency and consequently minimising the overhead of detecting these inefficient routes. Actually, ORMAD tries to prevent the frequent inviting of a GRDP in case of link failures. In order to maximise E_{ratio} of ORMAD against other extensions in (6.33), T_e should be minimised as less as possible so that $T_m << T_o$. This result is expected because waiting for longer time in a RMP may lead to receive more inefficient routes due to mobility and larger hop counts of the detected subroutes.

From (6.28), (6.30), and (6.32) it can be concluded that both M_t and M_n can be affected by η, μ and T_m. They cannot be affected by T_o. Also, it is shown from the equations that route efficiency, E, cannot be affected neither by η, μ, T_o nor T_m. It is affected mainly by the value of M_{em} which is affected by H_{mav} that is expressed in (6.23).

6.8 Multipath Degree λ

λ is defined earlier in this chapter as the Multipath Degree, MDG, of a multipath routing protocol. It is a new input parameter defined in this chapter (another novelty aspect) for testing the performance of a multipath routing protocol depends on the two new performance metrics, M_t and E. As shown in (6.34), the input parameter of MDG combines - in a qualified manner - three input parameters that are commonly used for testing and evaluation in MANETs routing protocols, mobility connectivity and waiting time ratios. The ideal case of a simulation or a real environment can be indicated to by the highest λ, which means the highest connectivity, the lowest mobility, the longest waiting time T, see Equation (6.34).

A multipath routing protocol can be measured by the total number of routes and the route efficiency of multiple routes detected by applying the routing protocol in different scenarios of MDG which are varying from high to low. As shown in (6.9), there are two types of MDGs in a multipath routing protocol, λ_o and λ_m associated with the two routing processes, RDP and RMP respectively. M_t can be maximised if MDGs λ_o and λ_m are both in the ideal case. Generally, λ can be written as in (6.34):

$$\lambda = \frac{\eta T}{\mu} \tag{6.34}$$

Suppose that it is required to test the rate of change of λ in terms of η, μ, and T depending on (6.34). It can be analyzed as follows:

- $\frac{\partial \lambda}{\partial \eta}$ and $\frac{\partial \lambda}{\partial T}$: λ has a linear relationship with the two parameters η and T, thus $\partial \lambda$ with respect to each one of them is a constant.

$$\frac{\partial \lambda}{\partial \eta} = \frac{T}{\mu}, \quad \mu \text{ and } T = constant,$$

$$\frac{\partial \lambda}{\partial T} = \frac{\eta}{\mu}, \quad \mu \text{ and } \eta = constant$$

- $\partial \lambda$ with respect to μ: $\frac{\partial \lambda}{\partial \mu}$ is derived as in (6.35):

$$\frac{\partial \lambda}{\partial \mu} = -\frac{\eta T}{\mu^2} \tag{6.35}$$

Where η and T are constants.

In order to detect the maximum value of λ in (6.35), the following condition should be met:

$$\frac{\partial \lambda}{\partial \mu} = 0 \Longrightarrow \mu = 0$$

This is not valid in the MANET's real world, so it is more suitable for the condition to be as in (6.36):

$$\mu = \mu_o \tag{6.36}$$

Where μ_o is a very small value (e.g. $\mu_o \in]0, 0001]$).

6.9 General Discussion

An analytical model is presented in this chapter for the whole process of ORMAD approach as a multipath extension to AODV protocol in MANETs. The analytical model describes how the two main core phases of ORMAD; RDP and RMP describes interact with each other with regard to the total number of detected routes and the route efficiency. The analytical model of ORAMD is implemented and tested to prove the behaviour of the total number of multiple routes and the route efficiency in terms of different scenarios of connectivity, mobility, and route reply waiting time.

The analytical model of ORMAD is tested on 6561 records of testing data using Matlab 6.0 and evaluated for ORMAD against multipath extensions to AODV of the third direction using two performance metrics; total number of routes and route efficiency. Results study of the testing and evaluation of the analytical model is presented later in Chapter 7

A novel aspect of the analytical model of ORMAD defines precisely the concepts of *Efficient Route (EFR)*, *Inefficient Route (IER)*, and *Route Efficiency (E)* in multipath ad hoc routing, especially for multipath AODV extensions. A set of definitions introduced for several terms in this analytical model of ORMAD can be applied not only to AODV multipath extensions but also to any reactive multipath protocol extensions in MANETs.

Another novel aspect of the analytical model of ORMAD defines the relationship between a *Global Waiting Time (GWT)* needed by a *Global Route Discovery Process (GRDP)* and a *Local Waiting Time (LWT)* needed by a *Local Route Discovery Process (LRDP)*. GWT is defined in this approach as the timeout applied by a source node while receiving RREP packets sent back by a destination (or by any intermediate node have a route to the destination) during a GRDP invoked due to a link failure. LWT is also defined in this analytical model as the timeout applied by an upstream node while receiving RREP packets sent back by a downstream node (or by any intermediate node that has a route to the downstream node) during a LRDP invoked due to a link failure.

Finally, the analytical model of ORMAD defines a new input parameter called *Multipath Degree (MDG)*, which is used to study the relationship between GWT and LWT. Multipath degree is a combination of three input parameters; waiting time, connectivity, and mobility ratios. The impact of these three input parameters on the total number of multiple routes detected due to a RDP or a RMP can be analyzed and tested using multipath degree. Multipath degree can be calibrated by varying these parameters to reach the optimum performance of the total number of routes in a multipath routing protocol. On the other hand, the impact of varying a LWT with respect to the corresponding GWT can be calibrated to reach the optimum route efficiency of alternative routes that are detected during a RMP. Utilising the combination of these three input parameters analytically in addition to the definitions of GRDP, LRDP, GWT and LWT can be applied not only to AODV multipath extensions but also to any reactive multipath protocol extensions in MANETs.

Chapter 7

Results Study of TRAODV and ORMAD Approaches

7.1 Introduction

The results study of this thesis is presented in this chapter including the results study and evaluation of TRAODV approach and its extension, ORMAD approach. Firstly, TRAODV performance is evaluated against AOMDV and MRAODV protocols by means of the simulations using NS2. Secondly, the results study of ORMAD approach is presented against the other multipath extensions to AODV protocol also by means of the simulations using NS2.

The simulations of the two protocols are based on the environment and the implementation conditions which are presented earlier in Chapter 3. As shown in Chapter 3, setting up the simulation environment (mobility and connection scenarios), figuring out input parameters, and defining performance metrics are discussed in details. All configurations applied to the experimental study in Chapter 3 are also applied here to TRAODV and ORMAD simulations.

Table 7.1 shows the fixed parameters configuration of the simulation while Table 7.2 shows the different scenarios of the simulation. The scenarios of network size (number of nodes) and fixed parameters are chosen based on the common scenarios used in the literatures of routing evaluation in MANETs, and the numbers of links and traffic sources are chosen so that they are uniformly distributed for each scenario of network size. Applying network sizes more than 100 nodes are not recommended in NS2 simulations because the simulator becomes slower at these scenarios. For this reason, the maximum network size used in this thesis is 100 nodes and the scenarios are uniformly distributed as 20, 50, 80, and 100 nodes.

As mentioned earlier in Chapter 3, the environment (Tables 7.1 and 7.2), input parameters, and performance metrics of the simulations of NS2 used in this thesis are inspired from the NS2 simulation environments that are commonly used with slight differences in so many literatures to evaluate routing protocols in MANETs (e.g. [13], [17], [105], and [124].

The boundaries of waiting time of RDP in TRAODV are chosen as 1 sec (AOMDV mode) and 20 sec (MRAODV mode). The upper boundary (20 sec) is the average waiting time of all scenarios MRAODV simulations by which the average of maximum number of multiple routes is reached (38.4375 routes). Threshold times of TRAODV are detected between the lower and the upper boundaries of RREP waiting time.

For ORMAD, the same boundaries are used for RREP waiting time in RDP (T_{w1}), however the boundaries of RREP waiting time in RMP T_{w2} are chosen between 1 and 5 seconds because the simulations show that waiting more than 5 seconds in a RMP is not feasible. The performance is affected dramatically as T_{w1} increases, especially in terms of average end-to-end delay overhead which is shown clearly later in the next section.

Table 7.1: Parameter configuration of the simulation

Dimensions	500m x 500m
Simulation time	250s
Radius of coverage area of each node	100m
Packet size	512 Bytes
Queue length	50 Packets
Queue buffering	Packets dropped for more than 30s
Send buffer size	60 Packets
The mobility model	Random waypoint model
Maximum speed of the nodes	20m/s
Packet transmission rate	10Kbps
Pause times	0s, 10s, 20s, 40s, 50s, 100s, 250s
MAC layer protocol	IEEE 802.11b (Max. trans. rate is 11Mbps)
Source type	CBR

Waiting time scenarios used are divided into two types. The first is T_{w1} which

Table 7.2: Scenarios of the simulation

Scenarios				
Nodes	20	50	80	100
Connections	5, 10, 15	10, 20, 30, 40	10, 30, 50, 70	10, 30, 50, 70, 90
Traffic sources	5, 10	10, 20, 30	10, 20, 30, 40, 50	10, 20, 30, 40, 50, 70
Boundaries of RREP waiting time (T_{w1}) for RDP 1- 20s				
Boundaries of RREP waiting time (T_{w2}) for RMP (ORMAD case) 1- 5s				

is used for TRAODV simulations and second is the combination between T_{w1} and T_{w2} which is used for ORMAD simulations. The results studies are presented by means of the total average value of each performance metric against mobility during all scenarios of the simulations. Results of number of routes and efficient routes are presented as needed versus number of connections or versus network size.

Usually, the results are presented in terms of packet delivery fraction (PDF), average end-to-end delay (AVGD), routing packets overhead (RPO), and throughput respectively. As an exception, we only present the results of the metrics which have more influence due to applying the approach. Fore example, the results of average end-to-end delay and routing packets overhead are sometimes focused more than packet delivery fraction and throughput because their behaviours are fluctuating between each protocol and its extension while the behaviours of packet delivery fraction and throughput are enhanced onward so that the extensions are almost better than the parent protocols in this context.

Finally, an analytical testing and evaluation are achieved numerically in this chapter for the analytical model of ORMAD which is developed in Chapter 6. The implementation is run on 6561 records of testing data using Matlab 6.0. Input parameters and performance metrics used for the testing process of the analytical model are described later in this chapter. The analytical model of ORAMD is implemented and tested to prove the behaviour of the total number of multiple routes and the route efficiency in terms of different scenarios of connectivity, mobility, and route reply waiting time.

7.2 Results Study of TRAODV Simulation

In this section, simulation results are firstly presented for the behaviours of total number of routes and number of efficient routes against waiting time of the RDP in TRAODV. Then, TRAODV is evaluated against AOMDV and MRAODV using the same simulation environment, input parameter, and performance metrics of the experimental study presented earlier in Chapter 3.

7.2.1 Number of routes against waiting time

The results study of TRAODV with regard to the total number of routes (M_{av}) and number of efficient routes, EFR, are presented here by estimating the average values of different scenarios (Table 7.2) associated with each number of nodes (n). Waiting time (T_{w1}) of RREPs in TRAODV, which is denoted by T_w along this section, is varied between 1 seconds (AODV mode) and 20 seconds (MRAODV mode) to detect a threshold time for each connection scenario. Threshold time is measured at the maximum number of efficient routes EFR (note: EFR is denoted in the figures as N_{av}). Hence, each connection scenario has a different value of T_w due to the differences in the number of connections for each scenario. Usually, number of connections is considered an indicator of the degree of connectivity in a network. As shown by the simulation results, the larger the number of connections the better the connectivity, and consequently the larger number of efficient routes. This result can be shown by the figures described bellow for different scenarios of n=50 and number of connections L=10, 20, 30, and 40 links. Since it represents a medium network size, this scenario is chosen as a sample of the results study that shows the behaviours of total number of routes and number of efficient routes against waiting time and number of connections in a network.

Connection scenario of $n = 50$, L=10:

Figure 7.1 shows the average total number of routes and efficient routes using TRAODV at the connection scenario of $L = 10$ links and a network size of $n = 50$. As shown in the figure, M_{av} increases as T_w increases while N_{av} increases with T_w until reaching the threshold time (T_w=5 sec) by which the maximum average number of efficient routes is reached (N_{av}=3.25 routes). After this point, N_{av} decreases as T_w increases.

The maximum average total number of routes is reached at T_w=20 sec (the case of MRAODV) by which M_{av}=6.75. However, this number includes both average numbers of efficient and inefficient routes which are estimated at this point (20 sec) as 2.5 and 4.25 respectively. These results are illustrated by Figure 7.2 in which the average numbers of efficient and inefficient routes are denoted by N_{av} and IER_{av} respectively.

As shown in the figure, IER_{av} increases as T_w increases while N_{av} starts decreasing after reaching the threshold time (T_w=5 sec). As shown in Figure 7.2, it should be observed that IER_{av} = N_{av} at T_w=9.5 sec where the two curves are intersected.

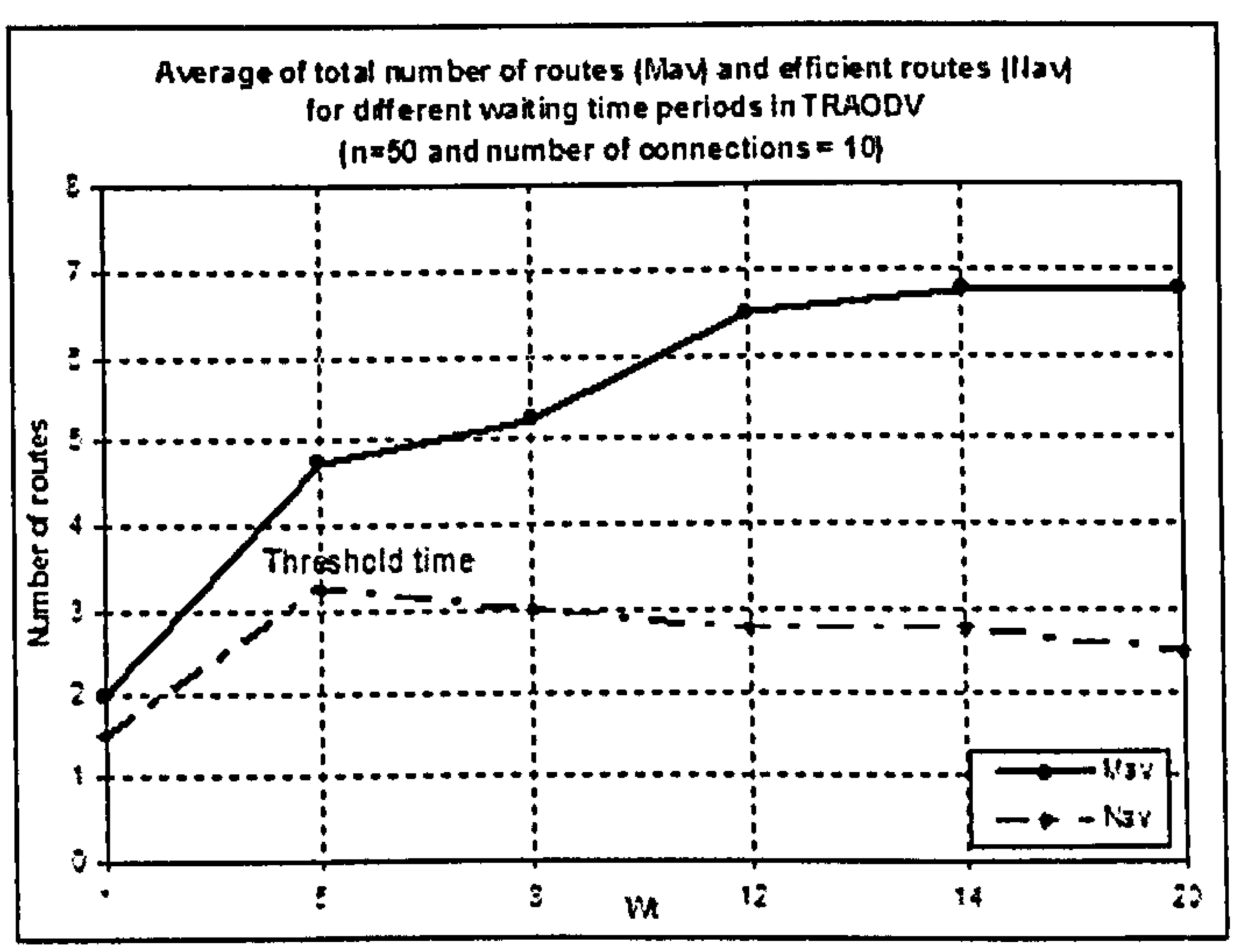

Figure 7.1: Average total number of routes and efficient routes at n=50, L=10

Connection scenario of n=50, L=20:

Figure 7.3 shows the average total number of routes and efficient routes using TRAODV at the connection scenario of L = 20 links and a network size of n = 50. As shown in

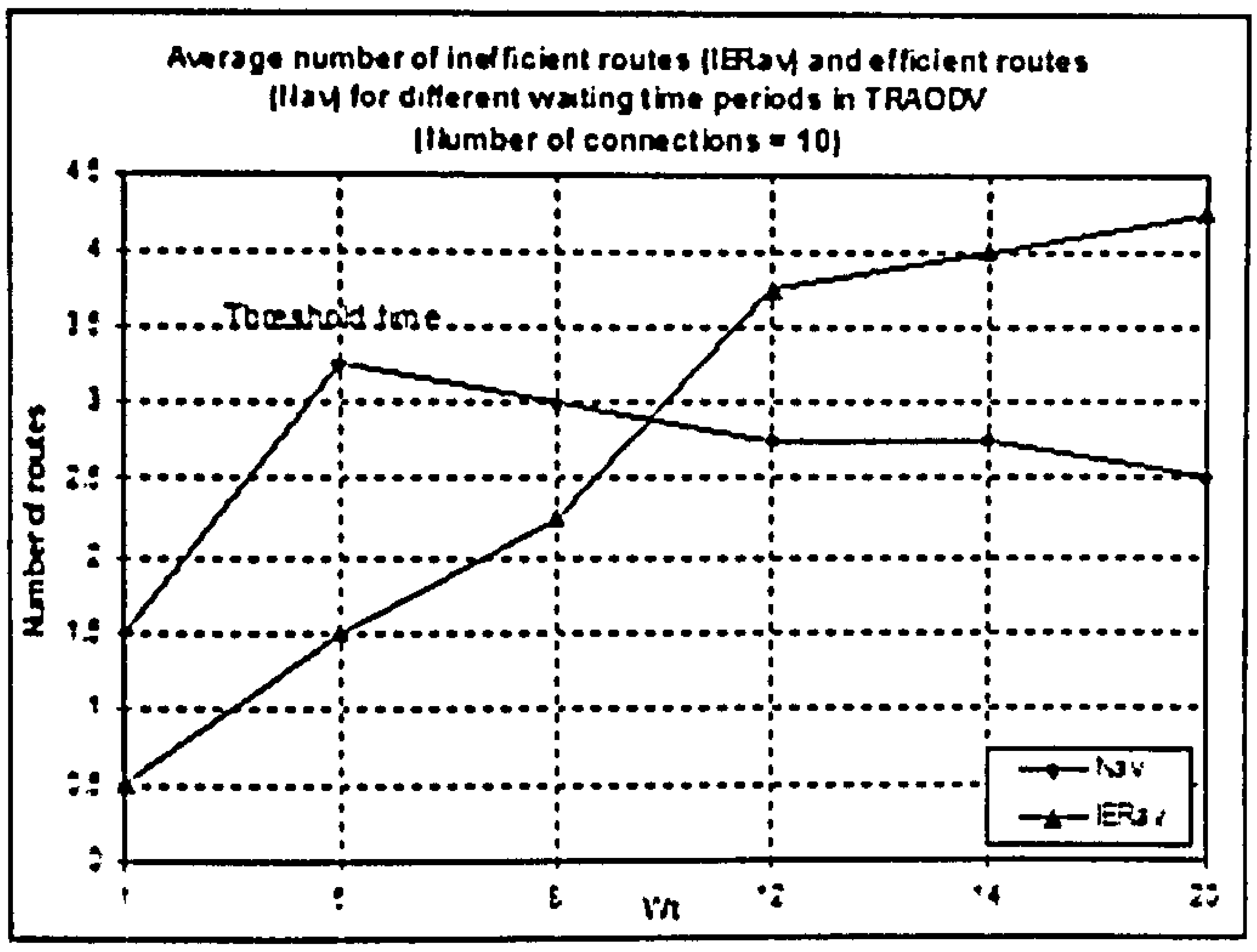

Figure 7.2: Average number of efficient and inefficient routes at n=50, L=10

the figure, M_{av} increases as T_w increases while N_{av} increases with T_w until reaching the threshold time (T_w=8 sec) by which the maximum average number of efficient routes is reached (N_{av}=6.25 routes). After this point, N_{av} decreases as T_w increases.

The maximum average total number of routes is reached at T_w=20 sec (the case of MRAODV) by which M_{av}=15.75. However, this number includes both average numbers of efficient and inefficient routes which are estimated at this point (20 sec) as 4 and 11.75 respectively. This results are illustrated by Figure 7.4 in which the average numbers of efficient and inefficient routes are denoted by N_{av} and IER_{av} respectively.

As shown in the figure, IER_{av} increases as T_w increases while N_{av} starts decreasing after reaching the threshold time (T_w=8 sec). As shown in Figure 7.4, it should be observed that $IER_{av} = N_{av}$ at at three waiting times; T_w=2.5, 5.5, and 11 sec where the two curves are intersected.

Connection scenario of n=50, L=30:

Figure 7.5 shows the average total number of routes and efficient routes using TRAODV at the connection scenario of L = 30 links and a network size of n = 50. As shown in

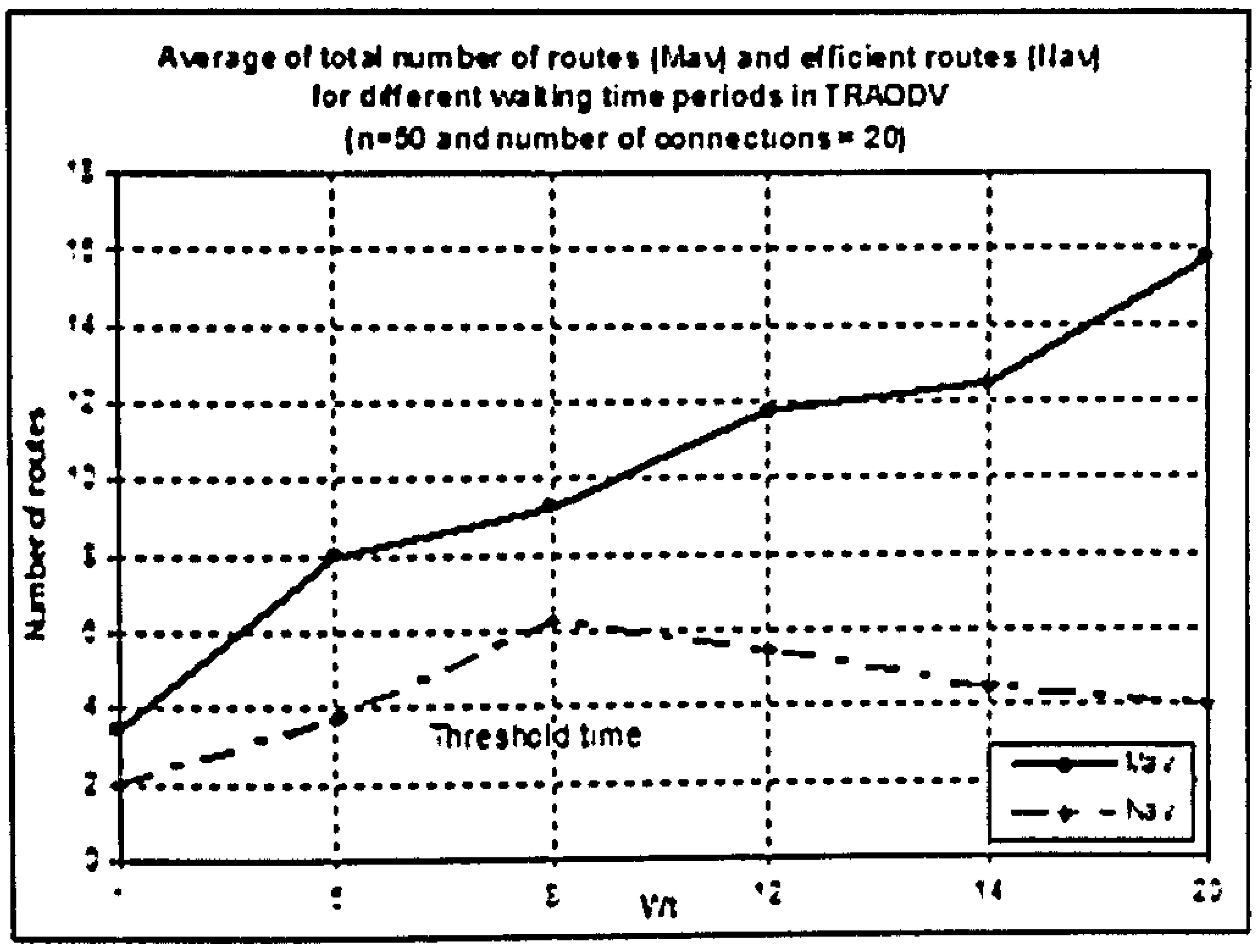

Figure 7.3: Average total number of routes and efficient routes at n=50, L=20

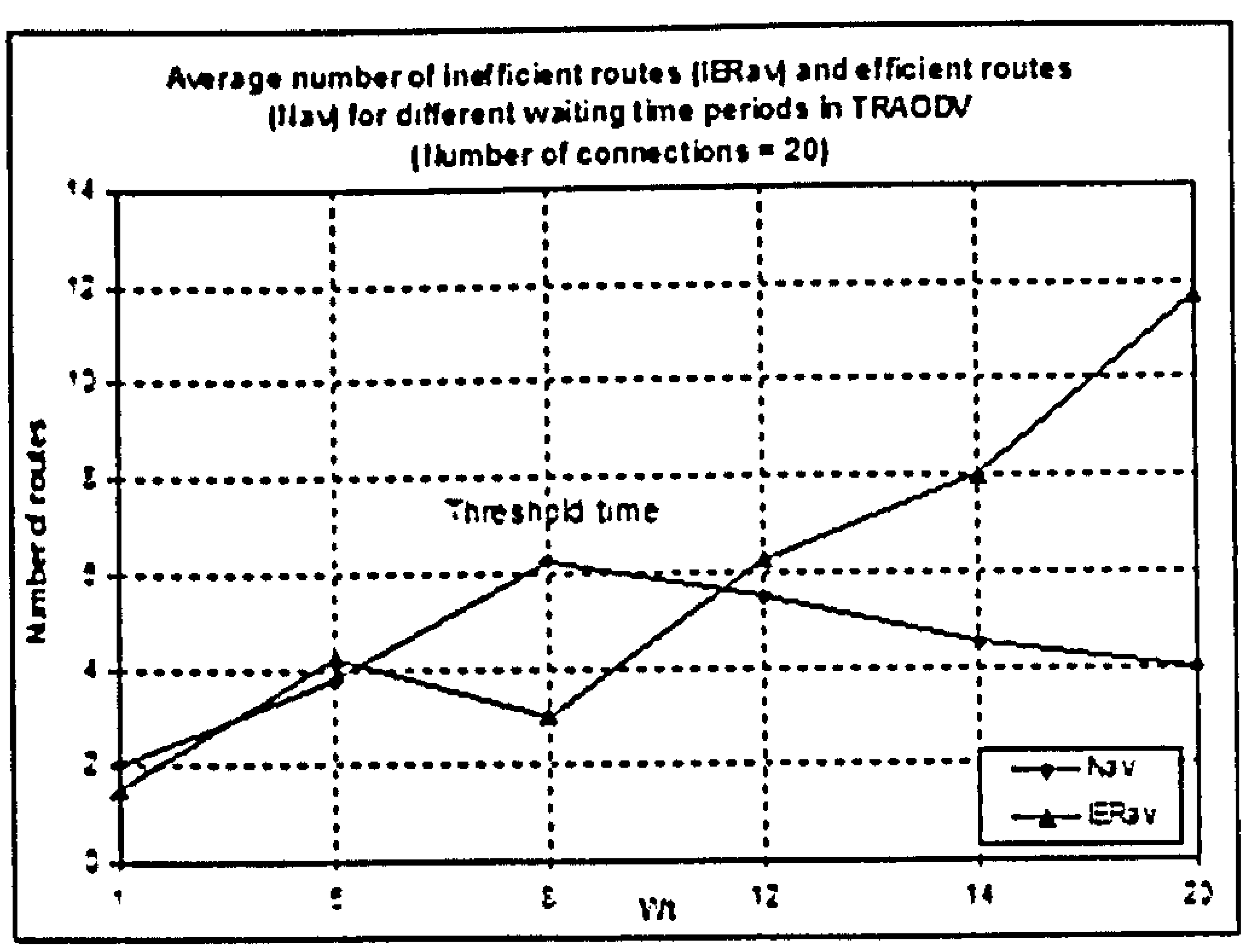

Figure 7.4: Average number of efficient and inefficient routes at n=50, L=20

the figure, M_{av} increases as T_w increases while N_{av} increases with T_w until reaching the threshold time (T_w=12 sec) by which the maximum average number of efficient routes is reached (N_{av}=9.25 routes). After this point, N_{av} decreases as T_w increases.

The maximum average total number of routes is reached at T_w=20 sec (the case of MRAODV) by which M_{av}=18. However, this number includes both average numbers of efficient and inefficient routes which are estimated at this point (20 sec) as 8 and 10 respectively. This results are illustrated by Figure 7.6 in which the average numbers of efficient and inefficient routes are denoted by N_{av} and IER_{av} respectively.

As shown in the figure, IER_{av} increases as T_w increases while N_{av} starts decreasing after reaching the threshold time (T_w=12 sec). As shown in Figure 7.6, it should be observed that $IER_{av} = N_{av}$ at at T_w=16 sec where the two curves are intersected.

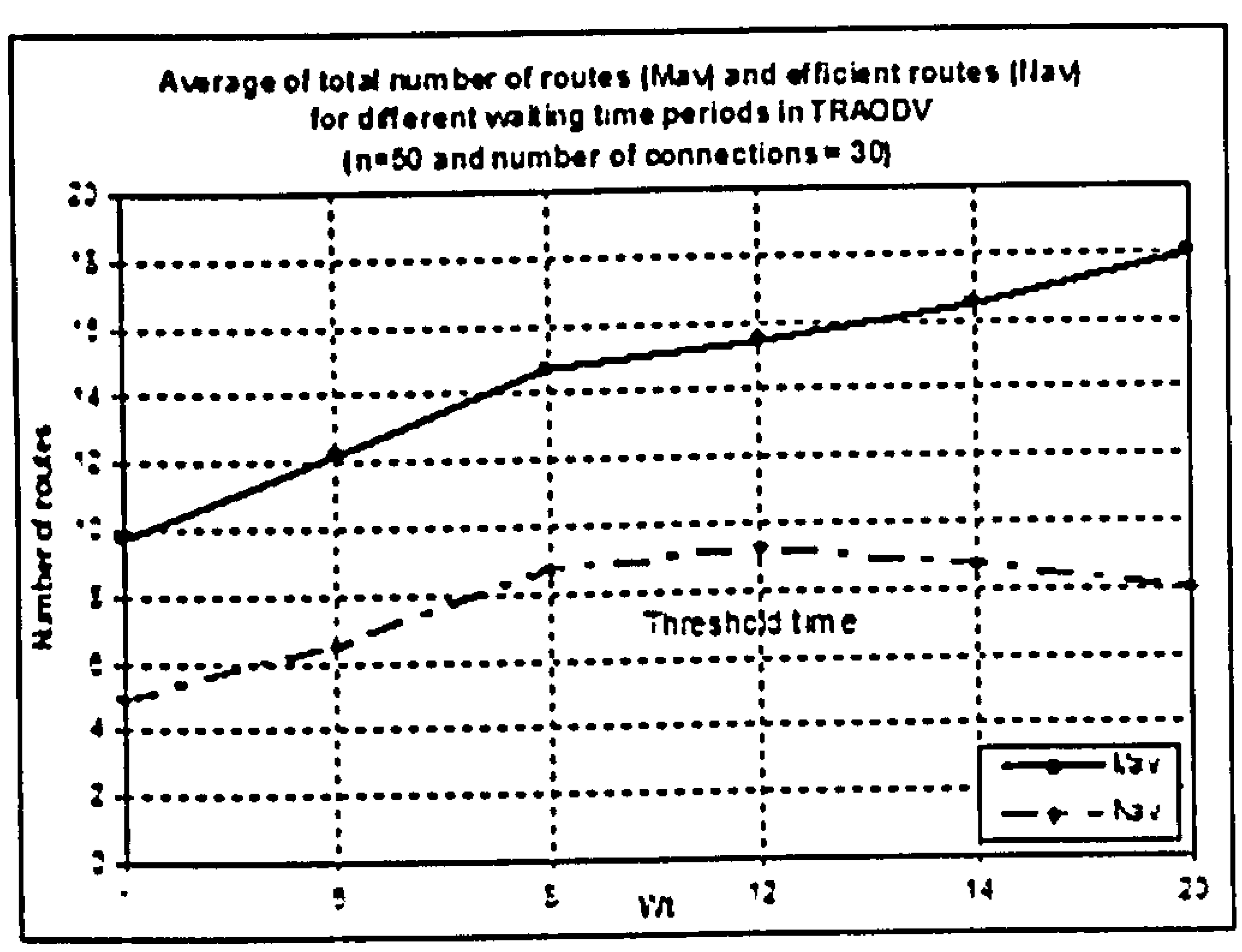

Figure 7.5: Average total number of routes and efficient routes at n=50, L=30

Connection scenario of n=50, L=40:

Figure 7.7 shows the average total number of routes and efficient routes using TRAODV at the connection scenario of L = 40 links and a network size of n = 50. As shown in the figure, M_{av} increases as T_w increases while N_{av} increases with T_w until reaching

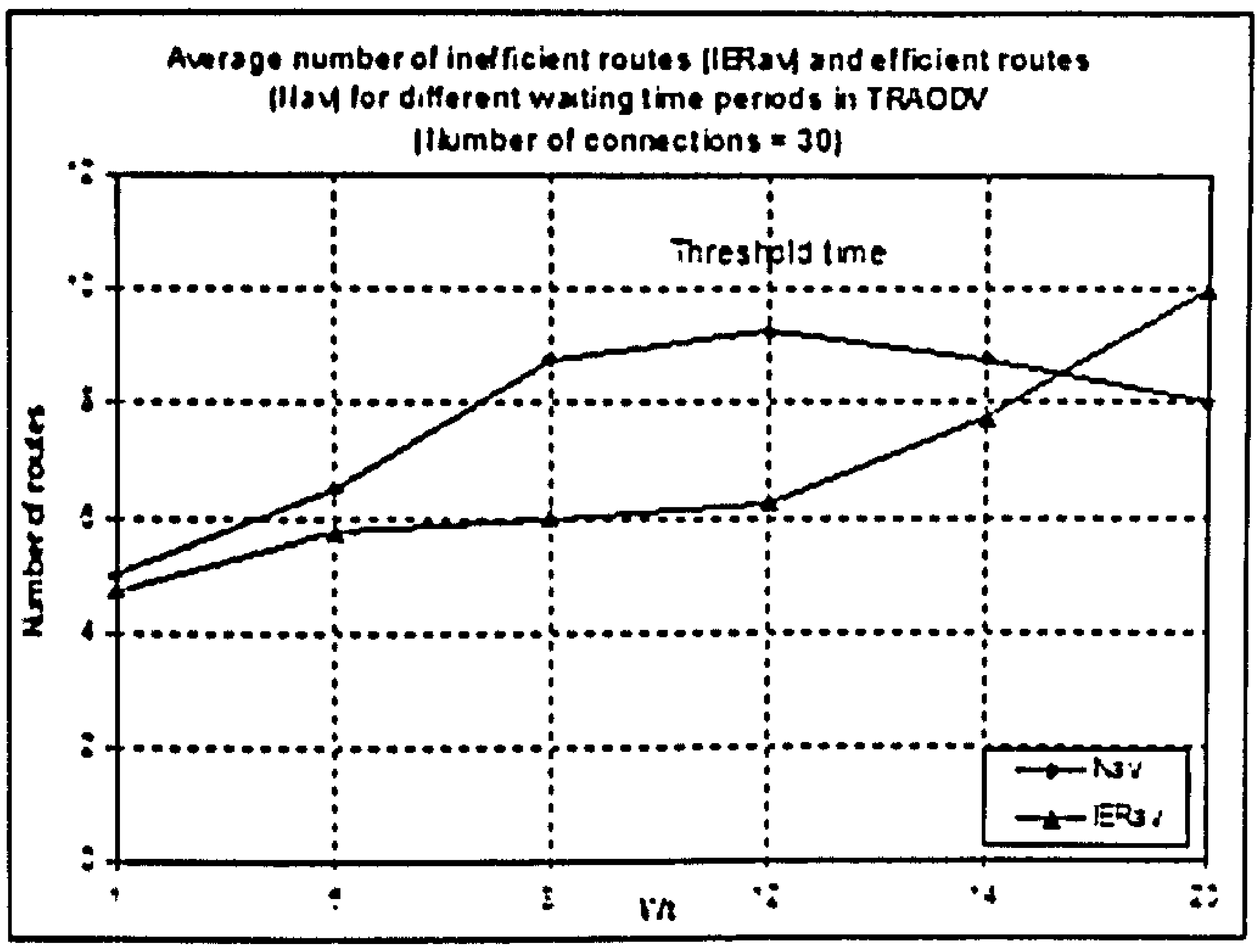

Figure 7.6: Average number of efficient and inefficient routes at n=50, L=30

the threshold time (T_w=14 sec) by which the maximum average number of efficient routes is reached (N_{av}=11.5 routes). After this point, N_{av} decreases as T_w increases.

The maximum average total number of routes is reached at T_w=20 sec (the case of MRAODV) by which M_{av}=26. However, this number includes both average numbers of efficient and inefficient routes which are estimated at this point (20 sec) as 9.75 and 16.25 respectively. This results are illustrated by Figure 7.8 in which the average numbers of efficient and inefficient routes are denoted by N_{av} and IER_{av} respectively.

As shown in the figure, IER_{av} increases as T_w increases while N_{av} starts decreasing after reaching the threshold time (T_w=14 sec). As shown in Figure 7.8, it should be observed that IER_{av} = N_{av} at at T_w=16 sec where the two curves are intersected.

Figure 7.9 shows the behaviour of threshold number of efficient routes and threshold waiting time against number of connections in TRAODV simulations at n=50. It is shown from the figure that threshold N_{av} and threshold T_w have proportional relationships with L so that they increase as L increases.

Generally, Figure 7.10 shows the behaviours of maximum number of routes,

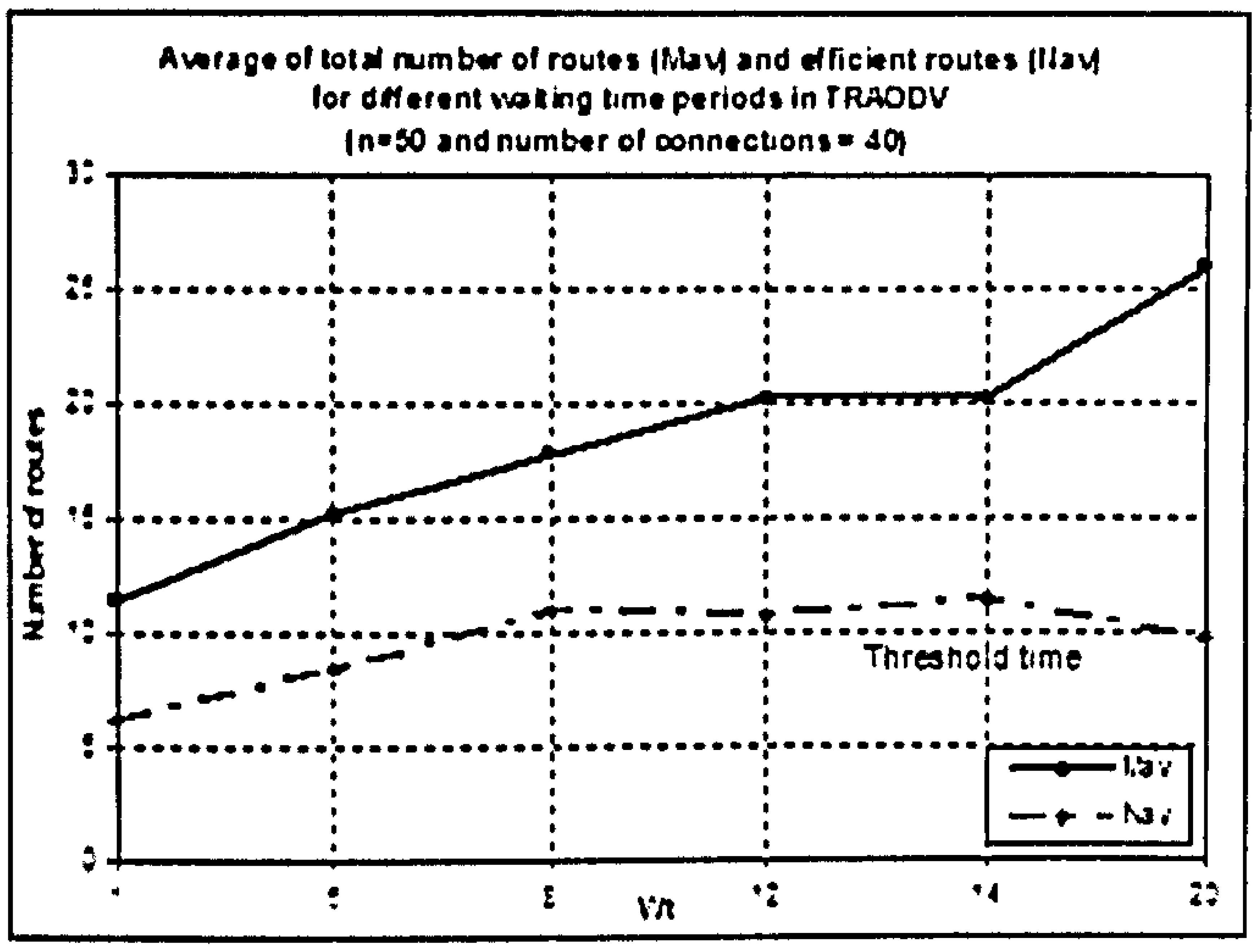

Figure 7.7: Average total number of routes and efficient routes at n=50, L=40

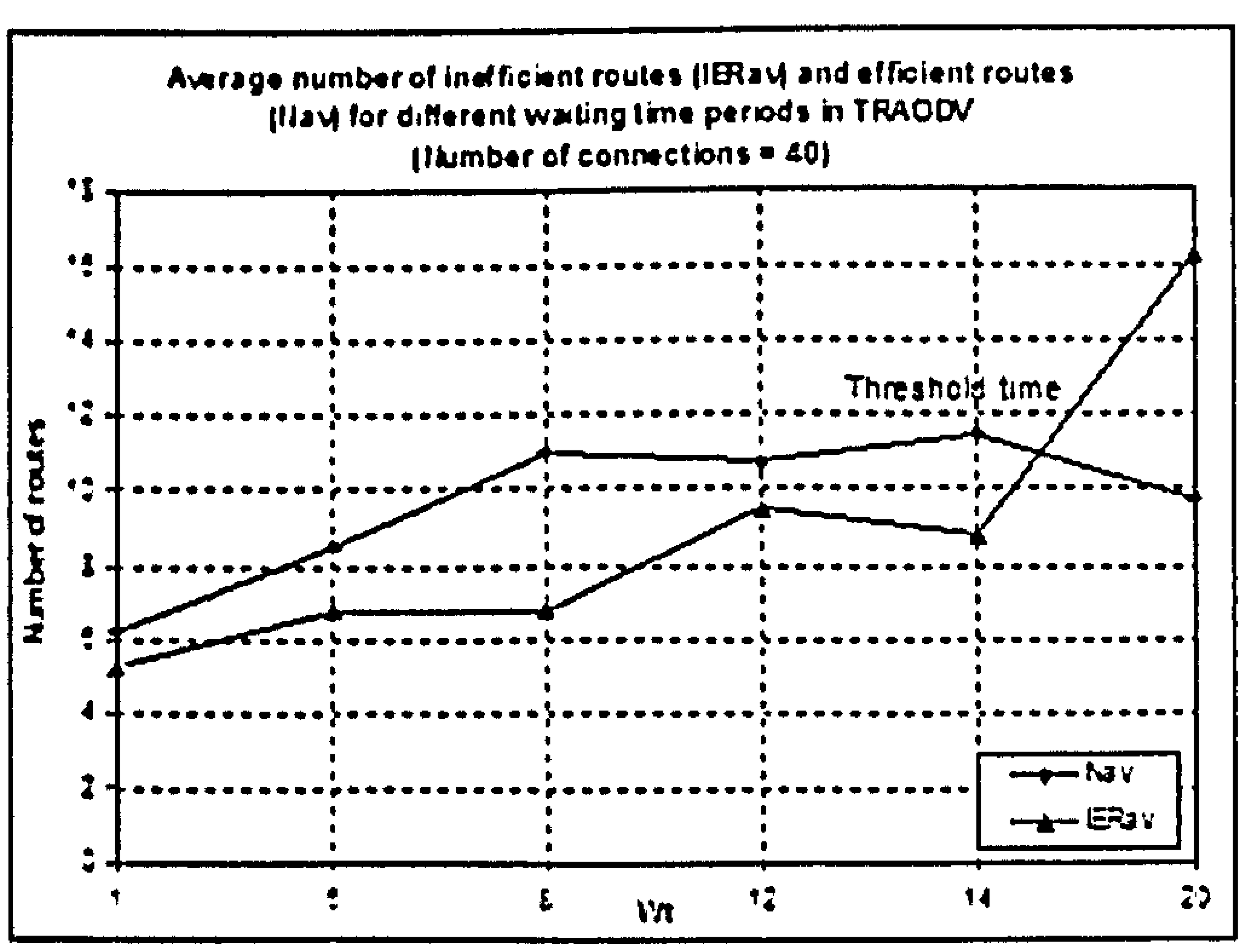

Figure 7.8: Average number of efficient and inefficient routes at n=50, L=40

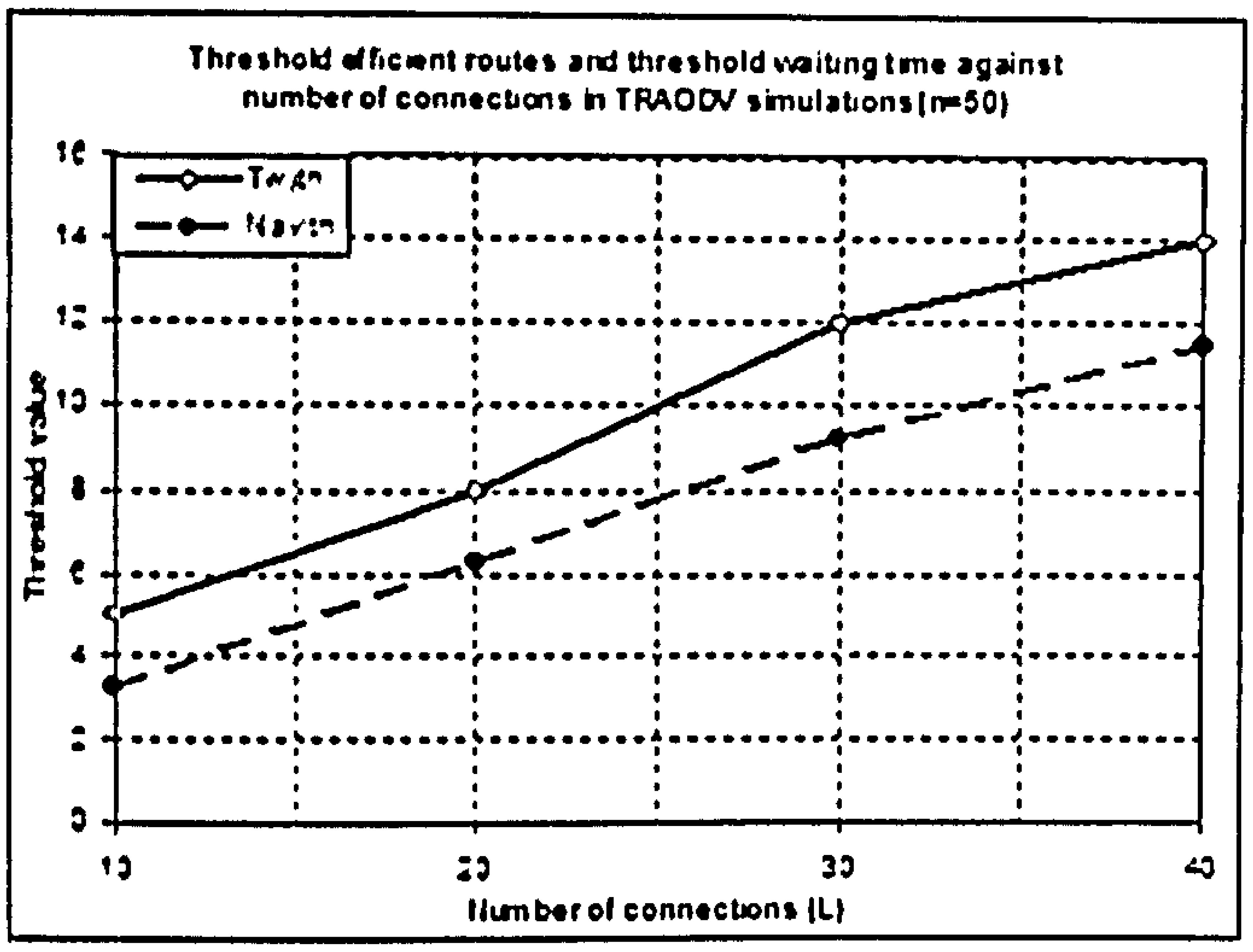

Figure 7.9: Behaviours of threshold N_{av} and threshold T_w versus number of connections (n=50)

threshold number of efficient routes, and threshold hop count against maximum number of connections in all network sizes (n=20, 50, 80, and 100). As shown by the figure, the maximum number of routes increases according to uniformly increasing in the network size while both threshold numbers of efficient routes and hop count increase slightly so that their curves have much less slope than the curve of the maximum number of routes. This means that as the network size increases, threshold number of efficient routes in TRAODV protocol converges to a saturation value. Hence, the average number of routes stored in a routing table of MRAODV protocol is always more than the number of routes in TRAODV. However, the routes stored and employed in TRAODV are only the efficient routes while MRAODV stores and employs all routes including efficient and inefficient routes. The evaluation of the performances of both protocols which is presented next in this section shows the effect of the routing mechanism mentioned above on the performance of each protocol.

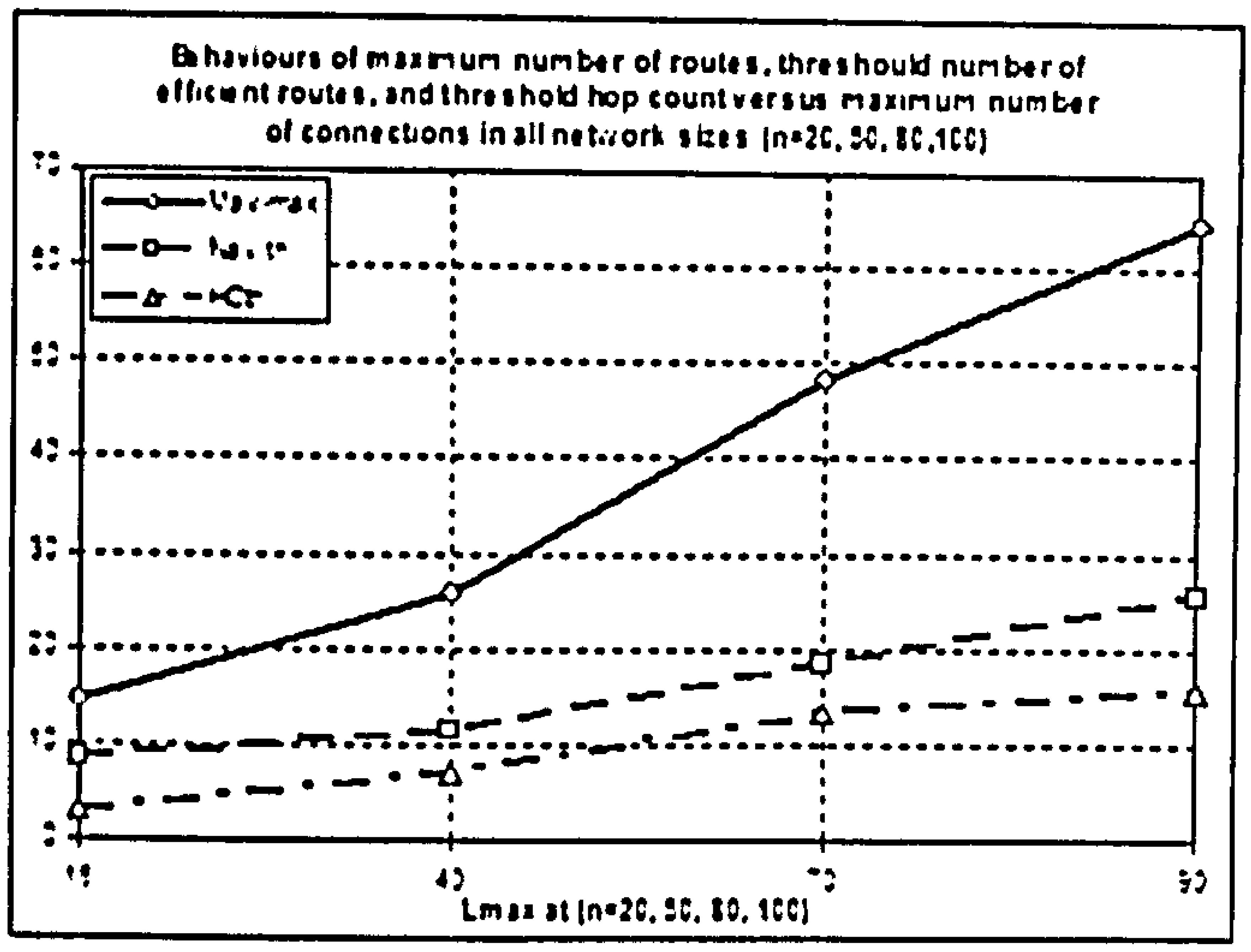

Figure 7.10: Behaviours of maximum M_{av}, threshold N_{av}, and HC_{th} versus network size

Results of changing the factor ϕ:

Figure 7.11 shows the behaviours of threshold N_{av} and threshold HC_{av} against ϕ in TRAODV simulations at n=50, L=40, T_w=14. As shown by the figure, there are proportional relationships between both threshold N_{av} and threshold HC_{av} and the factor ϕ. As ϕ increases, both threshold values of N_{av} and HC_{av} increase.

Figure 7.12 shows the average number of inefficient routes IER_{av} and efficient routes N_{av} against ϕ in TRAODV simulations at n=50, L = 40, T_w=14. It should be noticed that the summation of the numbers of efficient and inefficient routes is always equal to the total number of routes. As shown in the figure, the number of efficient routes increases as the factor ϕ increases and vice versa for inefficient routes. Increasing number of efficient routes to a large extent in the routing table is not an advantage in most multipath routing protocols in MANETs because they affect the performance of routing. The idea in TRAODV is to reach a threshold number of efficient routes that lead to the optimum performance. Figure 7.13 shows the average RPO and AVGD in TRAODV against ϕ in TRAODV approach at n=50, L=40, T_w=14. As shown in the figure, the optimum performance of TRAODV in terms of RPO and AVGD can be found in the range between 1 and 1.4 of the factor ϕ. For

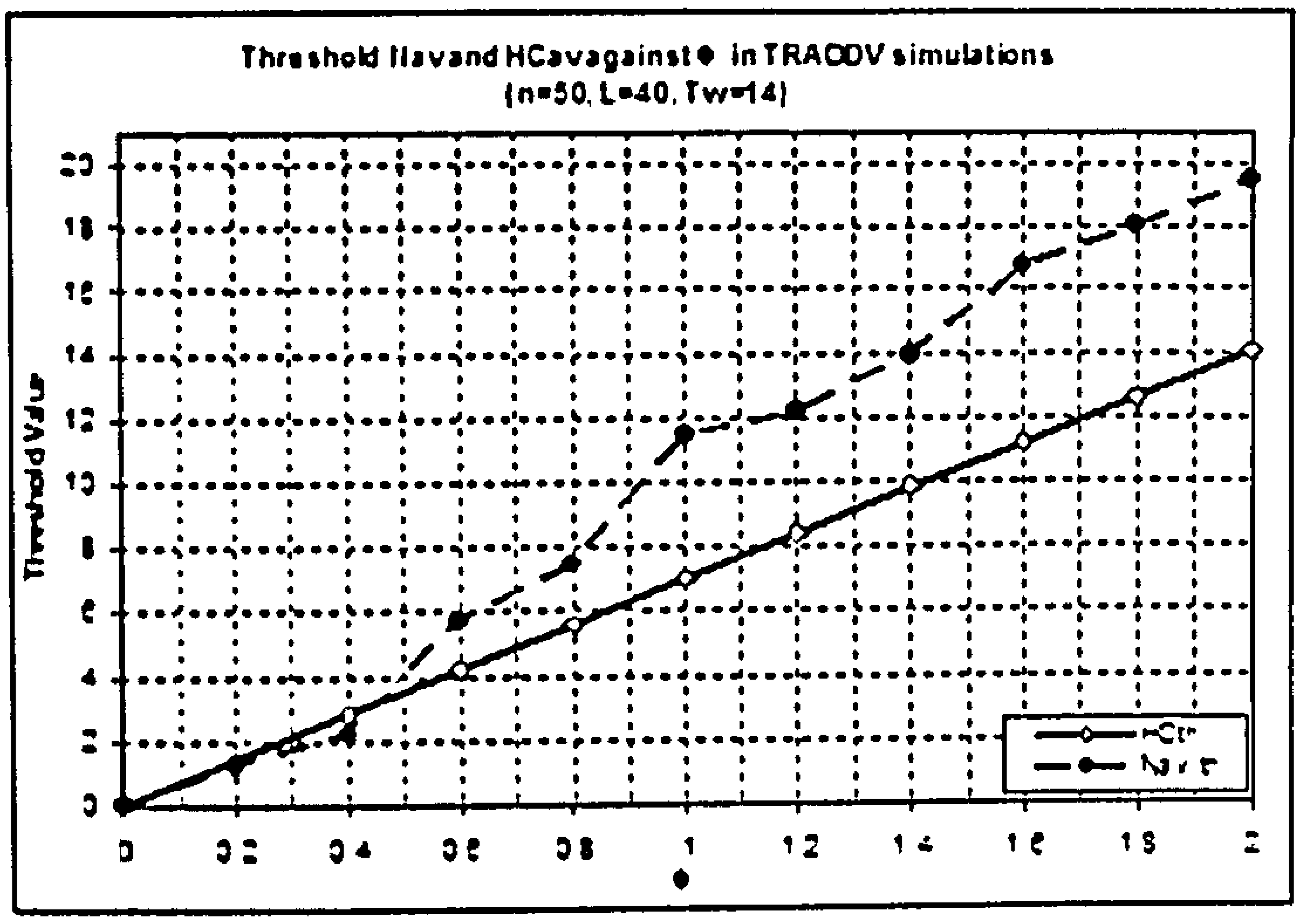

Figure 7.11: Threshold N_{av} and threshold HC_{av} against ϕ in TRAODV

these reasons, the default value ϕ=1 is used for testing and evaluation in this thesis for TRAODV and ORMAD approaches.

7.2.2 Evaluation of TRAODV against MRAODV and AOMDV

In this section, the average results of all scenarios of the simulations are presented. Results and evaluation of TRAODV performance against MRAODV and AOMDV are presented in terms of packet delivery fraction (PDF), end-to-end delay (AVGD), routing packets overhead (RPO), and throughput.

Figure 7.14 illustrates a comparison of TRAODV performance against MRAODV and AOMDV in terms of PDF by which the simulation results show that TRAODV slightly outperforms MRAODV and AOMDV in all mobility scenarios. As shown in the figure, the performance of MRAODV is slightly better than the performance of AOMDV in terms of PDF.

Figure 7.15 illustrates a comparison of TRAODV performance against MRAODV and AOMDV in terms of AVGD, by which the simulation results show that AODV

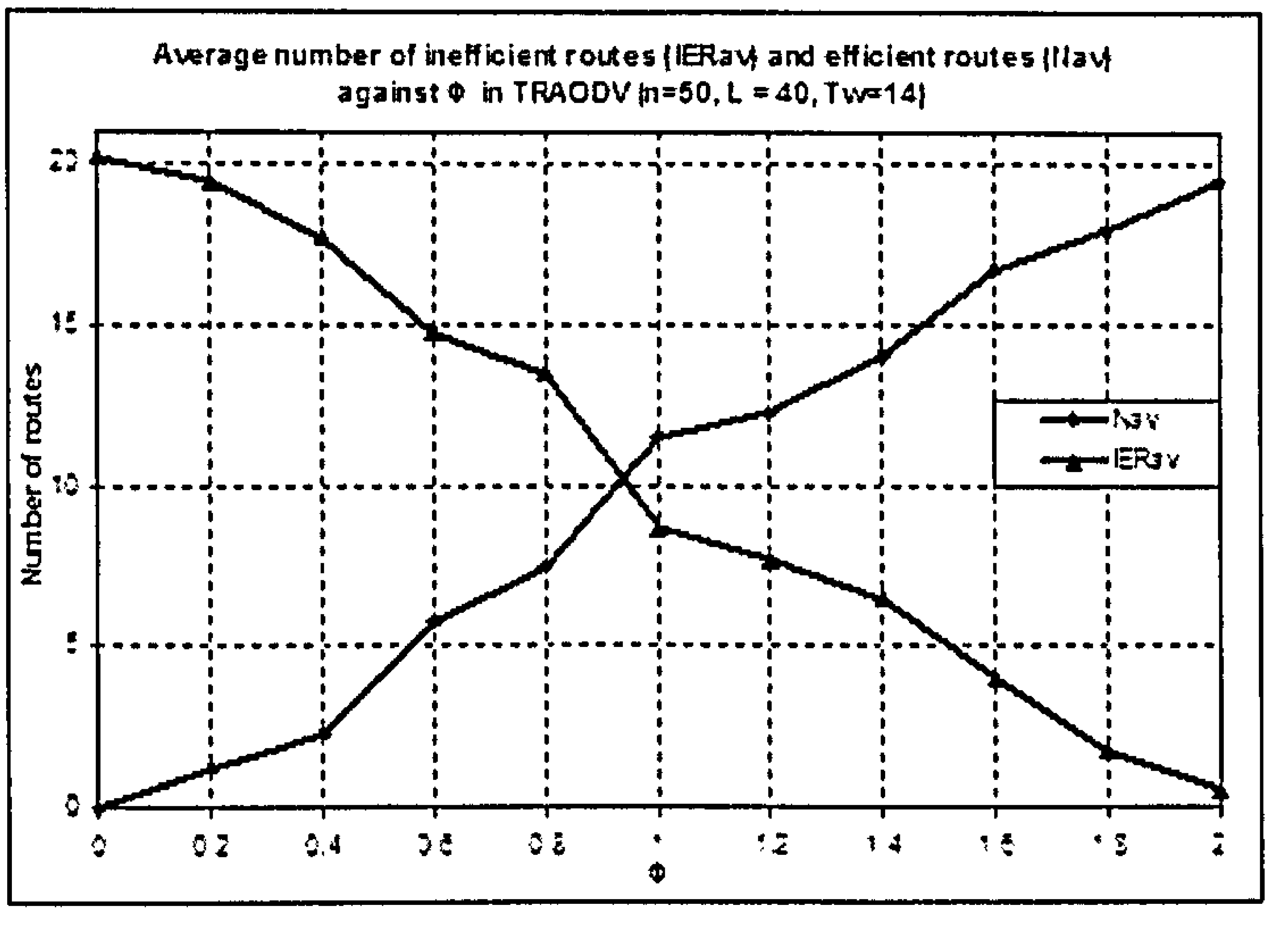

Figure 7.12: The average number of inefficient routes IER_{av} and efficient routes N_{av} against ϕ in TRAODV

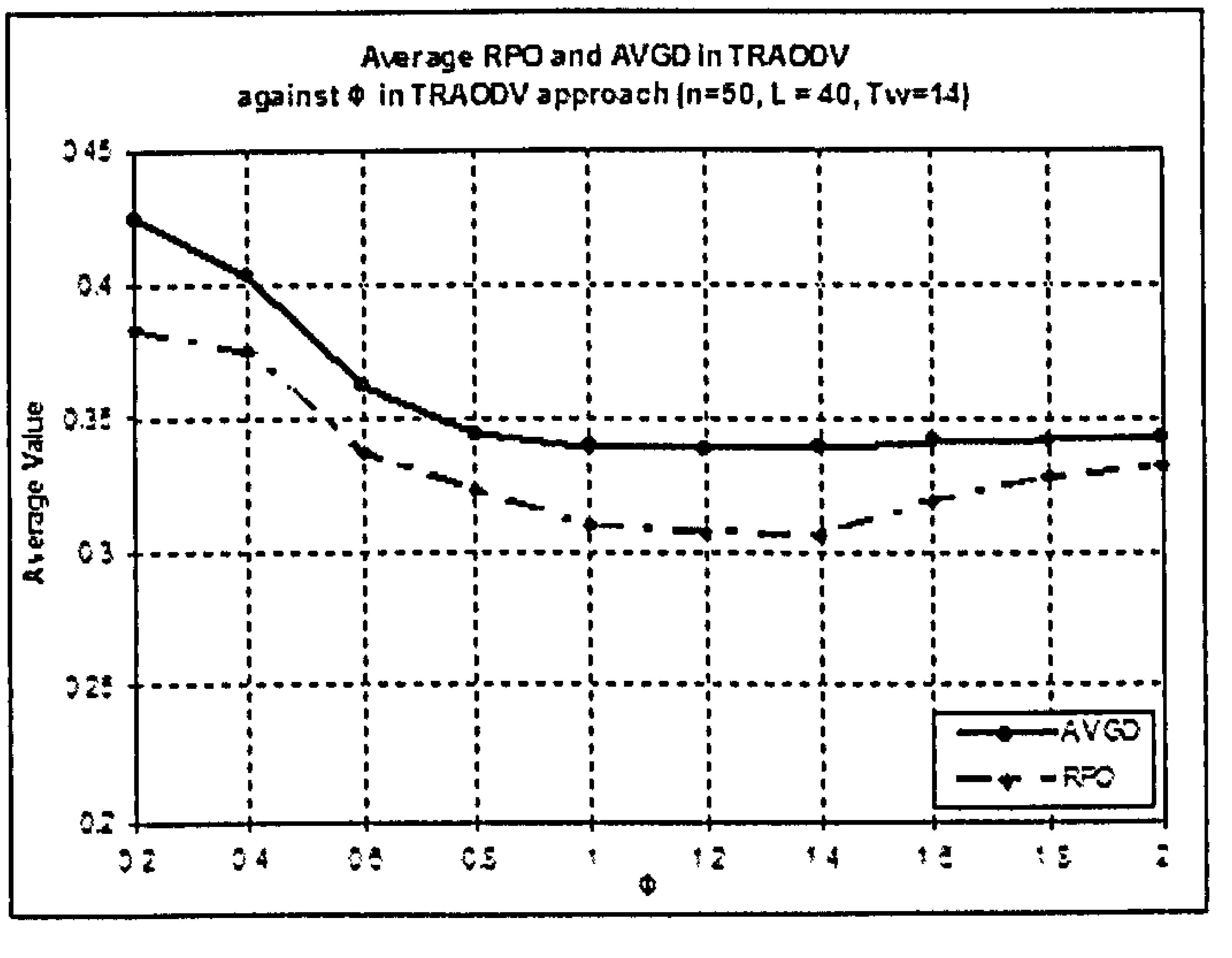

Figure 7.13: Average RPO and AVGD in TRAODV against ϕ in TRAODV approach

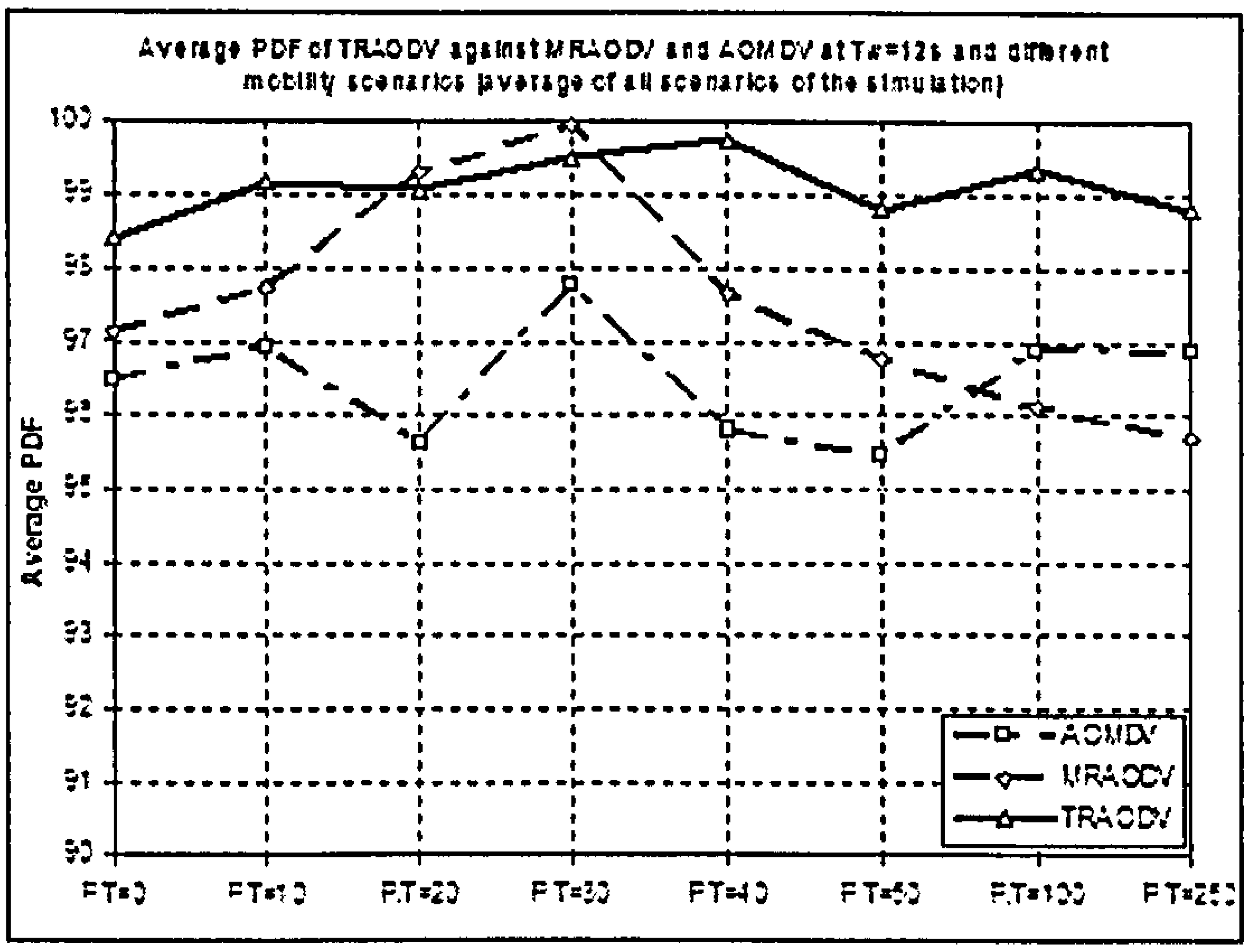

Figure 7.14: Average packet delivery fraction of TRAODV against MRAODV and AOMDV

outperforms both extensions MRAODV and TRAODV, especially in high mobility scenarios. However, as shown in the figure, the performances of MRAODV and TRAODV converge to the performance of AOMDV in medium and low mobility scenarios. In general, AOMDV is the best in terms of AVGD while MRAODV performs better than TRAODV in all mobility scenarios. This drawback of TRAODV with regard to AVGD is justified later in this section.

Figure 7.16 illustrates a comparison of TRAODV performance against MRAODV and AOMDV in terms of RPO, by which simulation results show that TRAODV outperforms MRAODV, especially in high mobility scenarios. As shown in the figure, the performance of MRAODV converges to the performance of TRAODV in low mobility scenarios. Hence, RPO is enhanced in MRAODV compared to AOMDV and enhanced more in TRAODV compared to MRAODV and this is the main advantage of TRAODV. Results of TRAODV simulations are more discussed later in this section with regard to RPO metric.

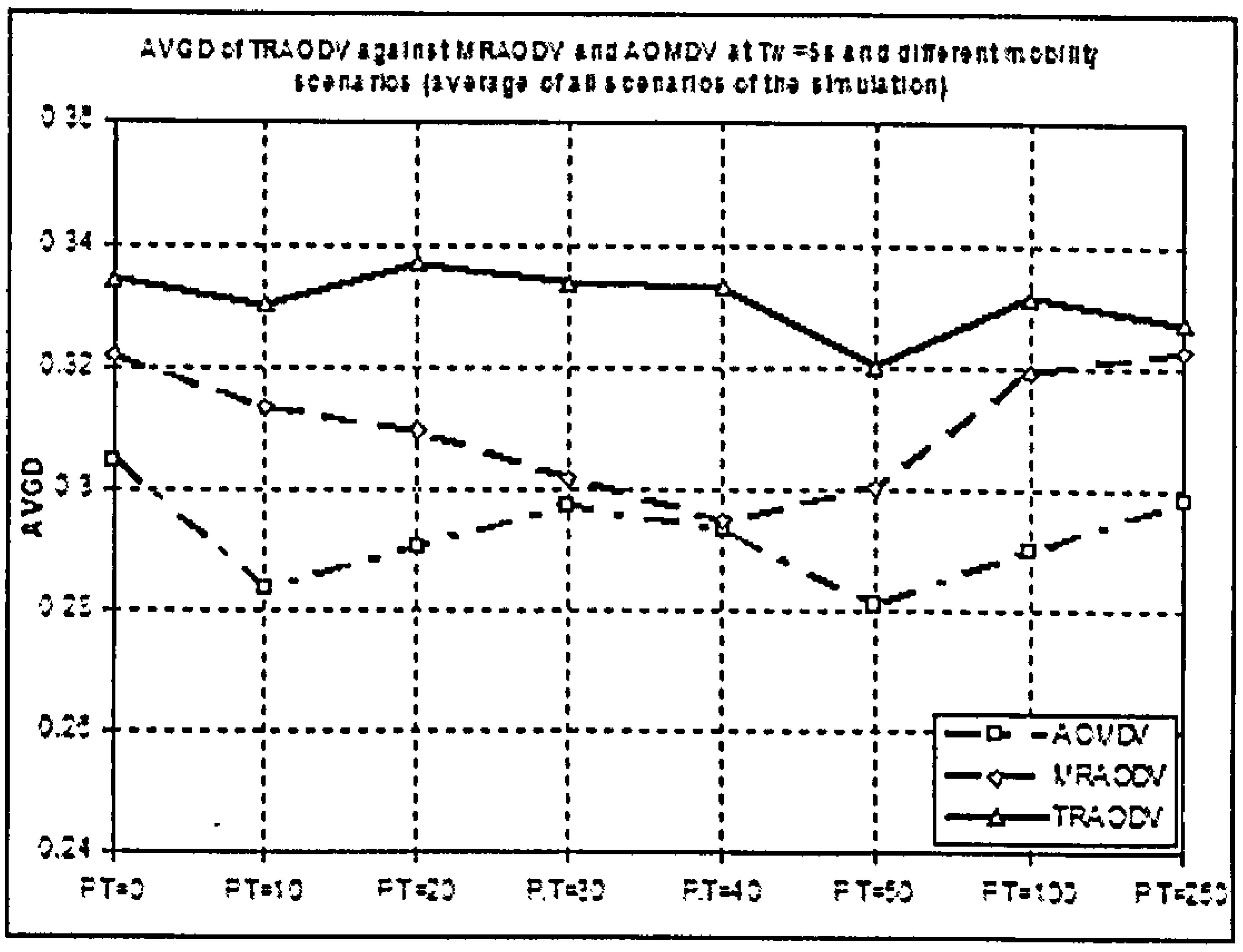

Figure 7.15: Average end-to-end delay of TRAODV against MRAODV and AOMDV

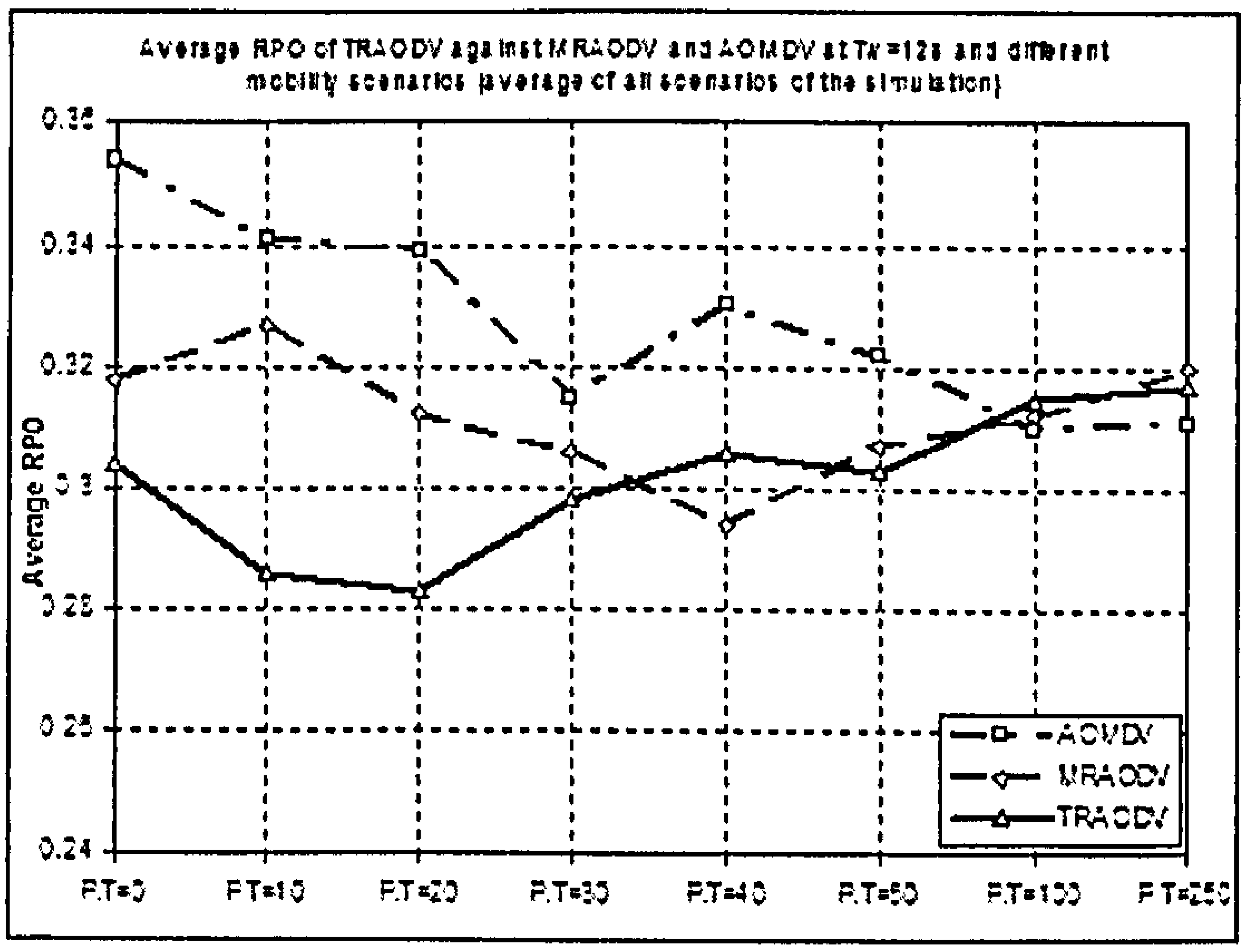

Figure 7.16: Average routing packet overhead of TRAODV against MRAODV and AOMDV

Figure 7.17 illustrates a comparison of TRAODV performance against MRAODV and AOMDV in terms of throughput, by which the simulation results show that TRAODV slightly outperforms MRAODV and AOMDV in all mobility scenarios. As shown in the figure, the performance of MRAODV is better than the performance of AOMDV in terms of throughput.

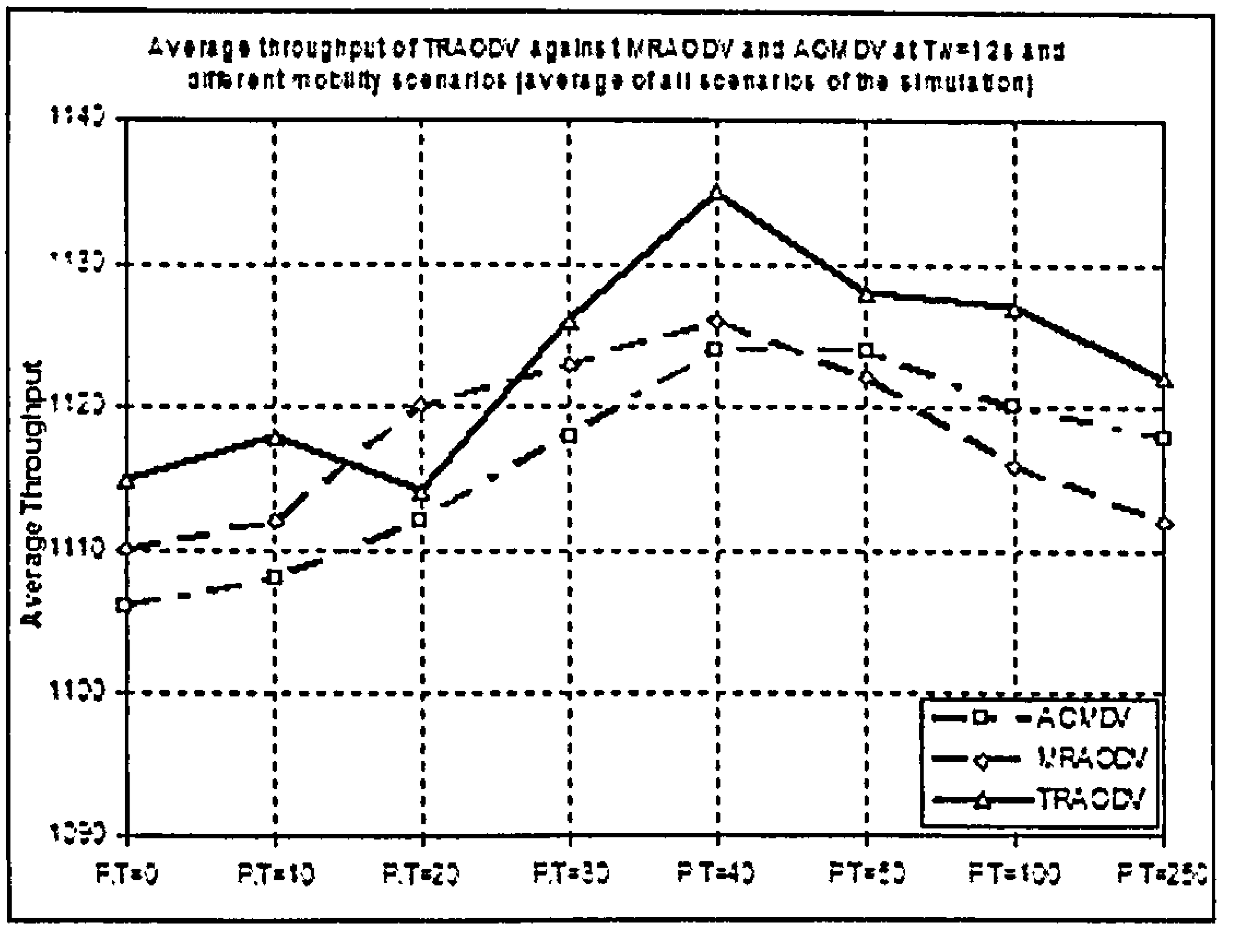

Figure 7.17: Average throughput of TRAODV against MRAODV and AOMDV

7.2.3 TRAODV performance against waiting time

Simulation results of TRAODV show that the performance metrics PDF, AVGD, RPO, and throughput are significantly affected by varying RREP waiting time in the route discovery process. For this reason, TRAODV performance is presented here against waiting time aiming at showing the effect of varying RREP waiting time in the performance of a multipath extension to AODV protocol.

Figure 7.18 shows the average performance of TRAODV in terms of PDF against waiting time based on the average simulation results of all scenarios. As shown in the figure, the maximum value of PDF is 103.625 which is reached at a threshold time of 12 sec (note: the higher the PDF the better the performance). As shown in the figure, PDF decreases while the waiting time moves to 1 sec (the case of AOMDV) and 20 sec (the case of MRAODV). The worst case is reached at 1 sec which represents AOMDV case.

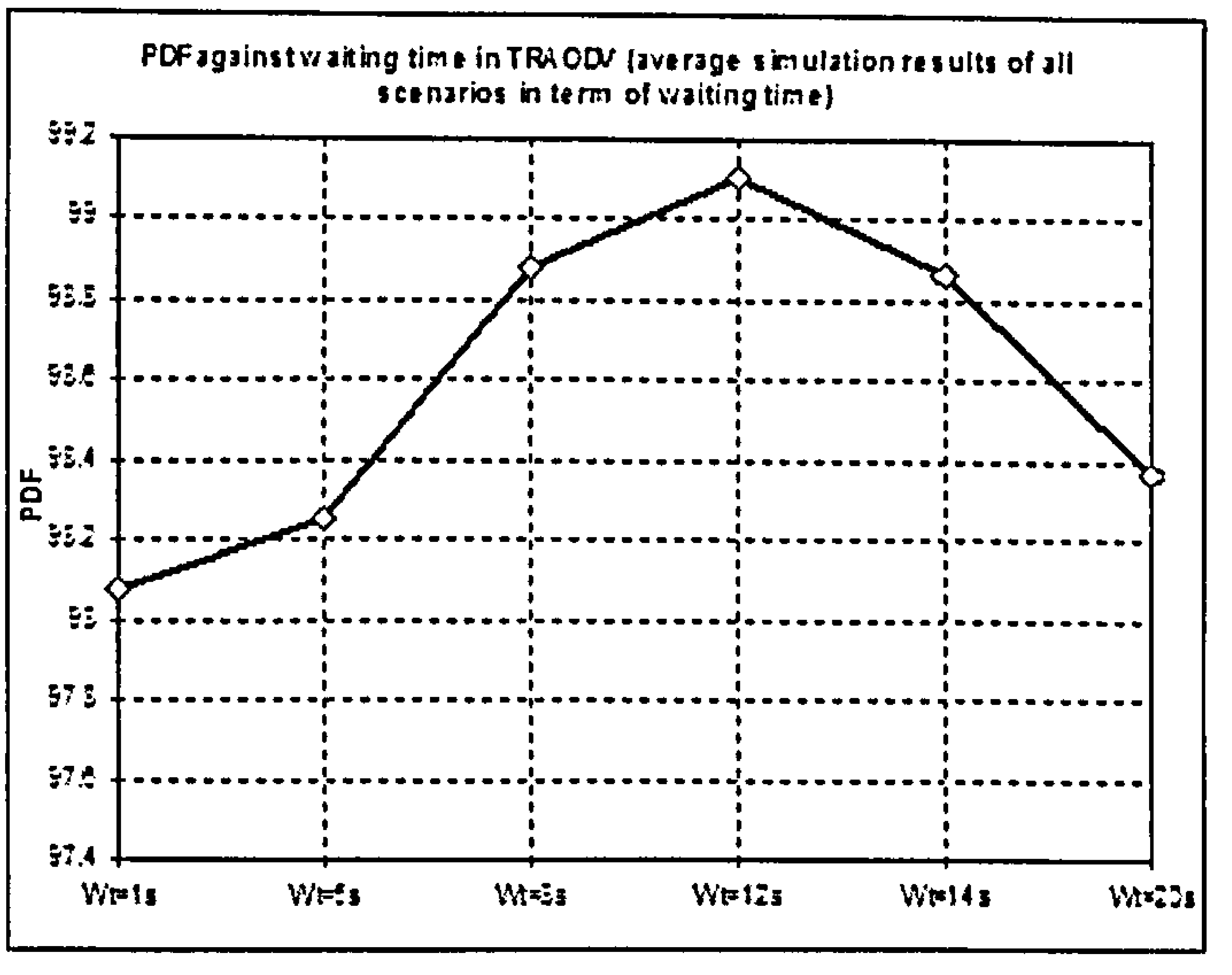

Figure 7.18: Average PDF versus waiting time in TRAODV

Figure 7.19 shows the average performance of TRAODV in terms of RPO against waiting time based on the average simulation results of all scenarios. As shown in the figure, the minimum value of RPO is 0.3015 which is reached at a threshold time of 12 sec (note: the lower the RPO the better the performance). As shown in the figure, RPO increases while the waiting time moves to 1 sec (the case of AOMDV) and 20 sec (the case of MRAODV). The worst case is reached at 20 sec (RPO=0.3409) which represents MRAODV case.

Figure 7.20 shows the average performance of TRAODV in terms of AVGD against waiting time based on the average simulation results of all scenarios. As shown in the figure, the minimum value of AVGD is 0.3309 which is reached at a threshold time of 5 sec (note: the lower the AVGD the better the performance). As shown in the figure, AVGD increases while the waiting time moves to 20 sec (the case of MRAODV) which is the worst case (AVGD=0.34225 at this point). From the figure,

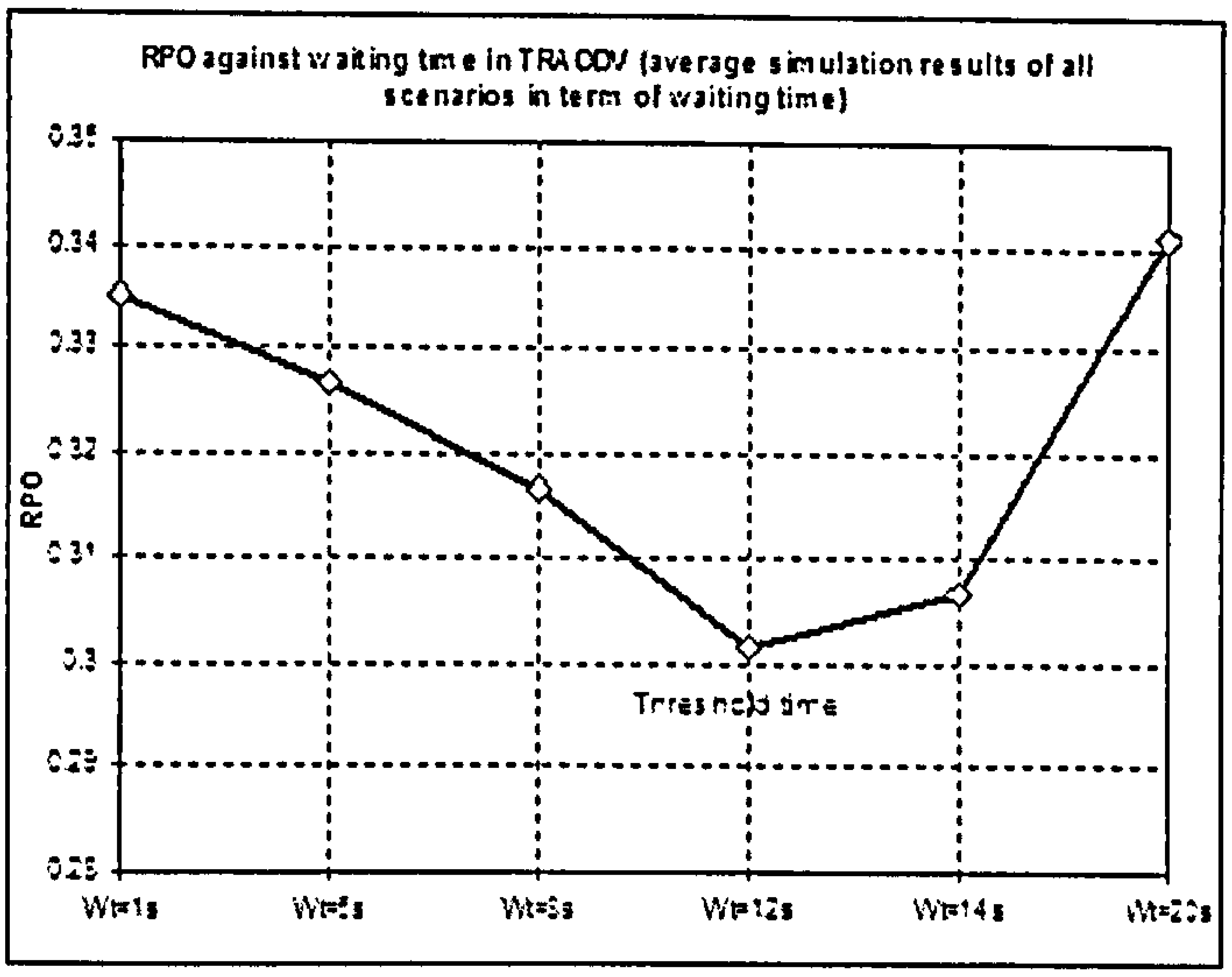

Figure 7.19: Average RPO versus waiting time in TRAODV

it is clear that AVGD becomes better near the case of AOMDV protocol which has the best performance in terms of AVGD amongst the three extensions to AODV.

Figure 7.21 shows the average performance of TRAODV in terms of throughput against waiting time based on the average simulation results of all scenarios. As shown in the figure, the maximum value of throughput is 1123.125 which is reached at a threshold time of 12 sec (note: the higher the throughput the better the performance). As shown in the figure, throughput decreases while the waiting time moves to 1 sec (the case of AOMDV) and 20 sec (the case of MRAODV). The worst case is reached at 20 sec which represents MRAODV case.

7.2.4 Discussion

The mechanism of TRAODV is that it calibrates the waiting time until receiving threshold number of efficient routes, which are only the routes that are stored in the routing table of the source node. As mentioned earlier in Chapter 4, simulations of TRAODV are carried out for different values of RREP waiting time in a range between 1 and 20 seconds. Different threshold waiting times are detected for different

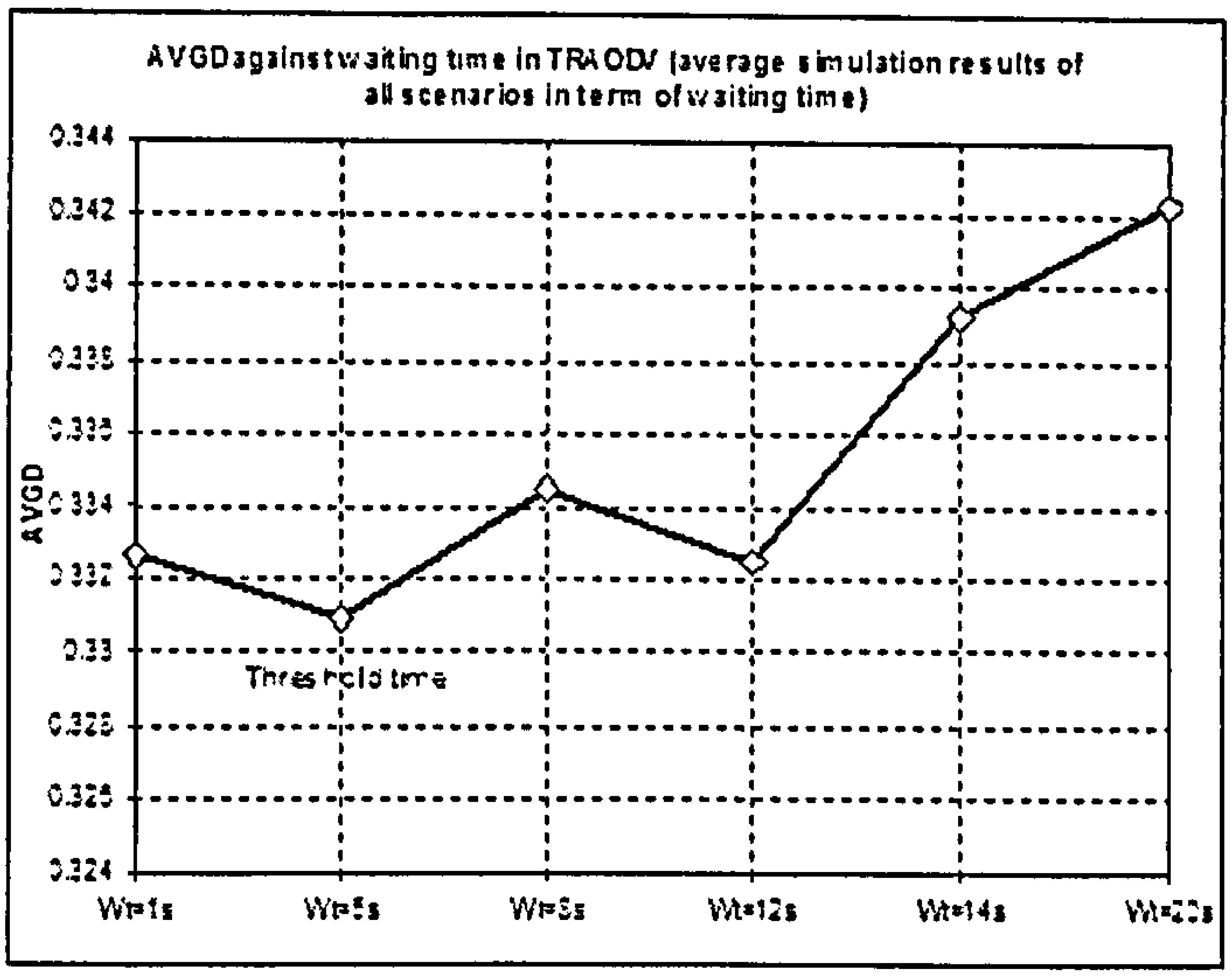

Figure 7.20: Average AVGD versus waiting time in TRAODV

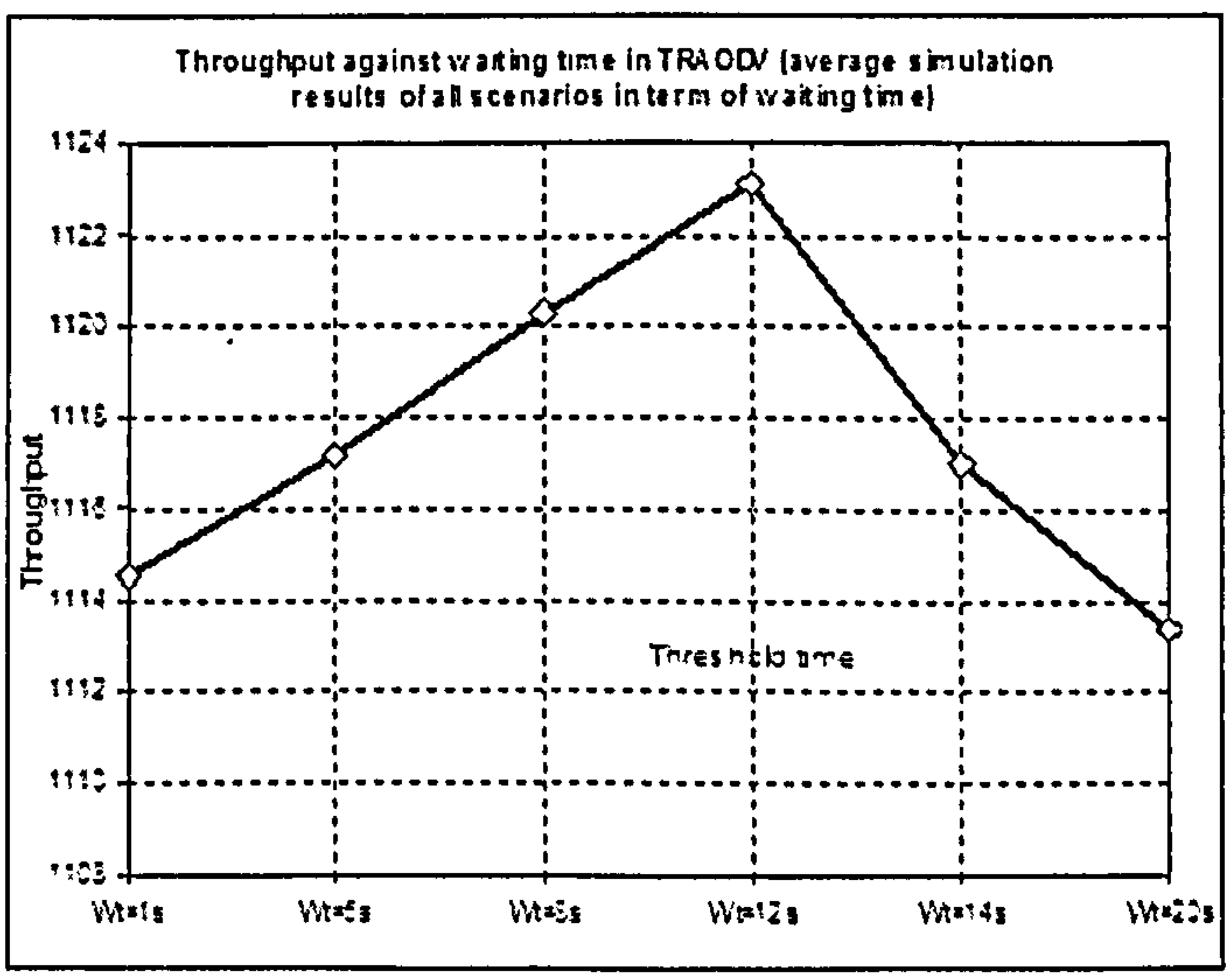

Figure 7.21: Average throughput versus waiting time in TRAODV

number of connections and the performance metric. Each threshold time is evaluated as the time by which the protocol TRAODV has the best performance in terms of the corresponding performance metric. As shown in the results and as illustrated by Figure 7.22, TRAODV has the highest performance of RPO compared to AOMDV and MRAODV with respect to TORA performance which is still the best in terms of RPO. AOMDV, MRAODV, and TRAODV have performances 76.78%, 81.55%, and 84.73% respectively with respect to TORA performance. TRAODV has an improvement of 3.18% in RPO compared to MRAODV. However, MRAODV is still better than TRAODV in terms of AVGD in which the performance of MRAODV is 22.69% with respect to the performance of the original protocol AODV, while the performance of TRAODV is reduced to 17.572%, the reduction is about 5.11% compared to MRAODV performance. Generally, AOMDV still has the best performance in terms of AVGD amongst the three extensions so that it performs 27.20% with respect to the performance of the original protocol AODV.

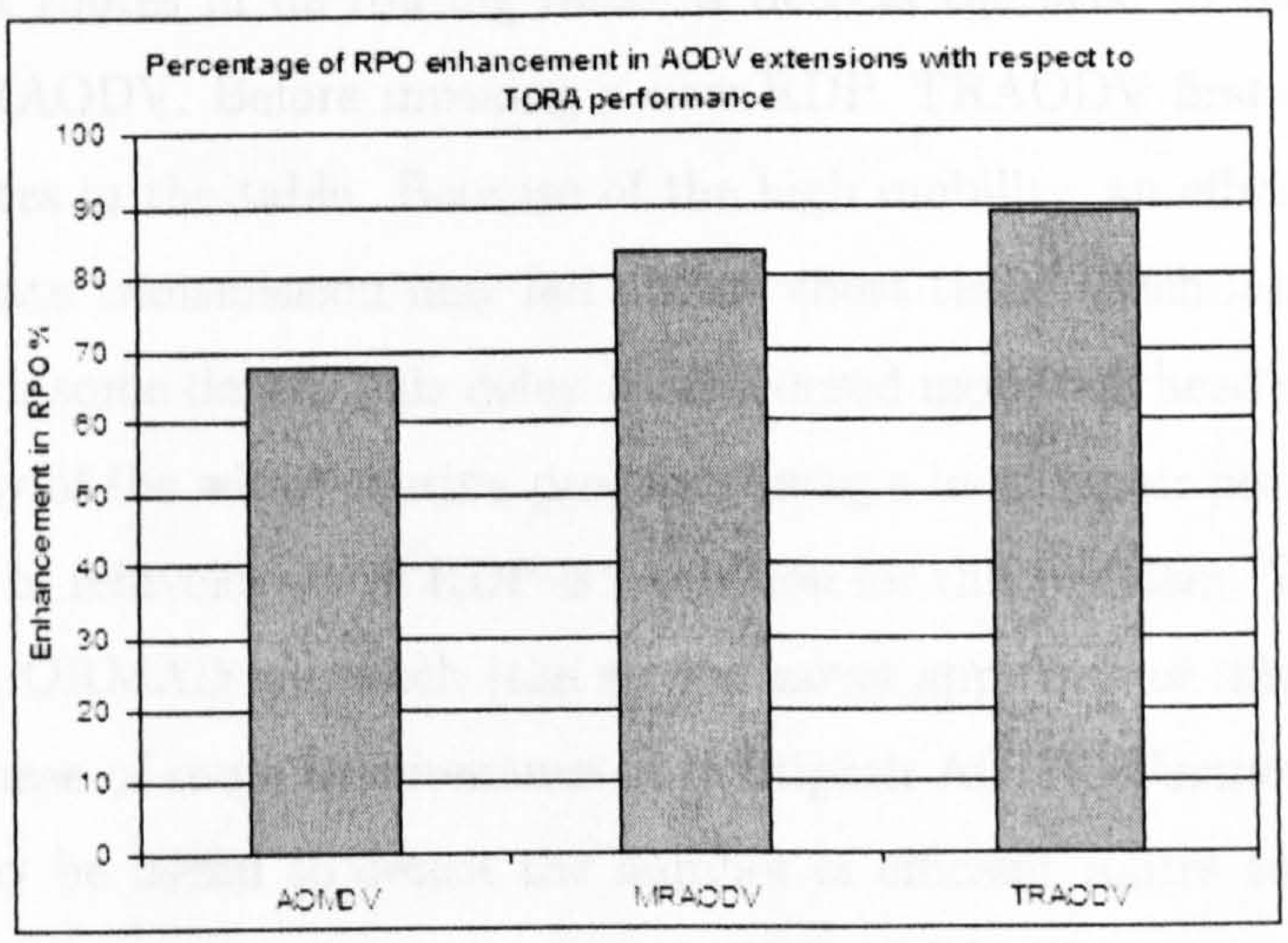

Figure 7.22: RPO in TRAODV compared to AOMDV and MRAODV

Figures 7.24, 7.25, 7.26, and 7.27 show the average performance of TRAODV in terms of PDF, AVGD, RPO, and throughput respectively compared to AODV, AOMDV, MRAODV, and the two traditional multipath protocols; DSR and TORA.

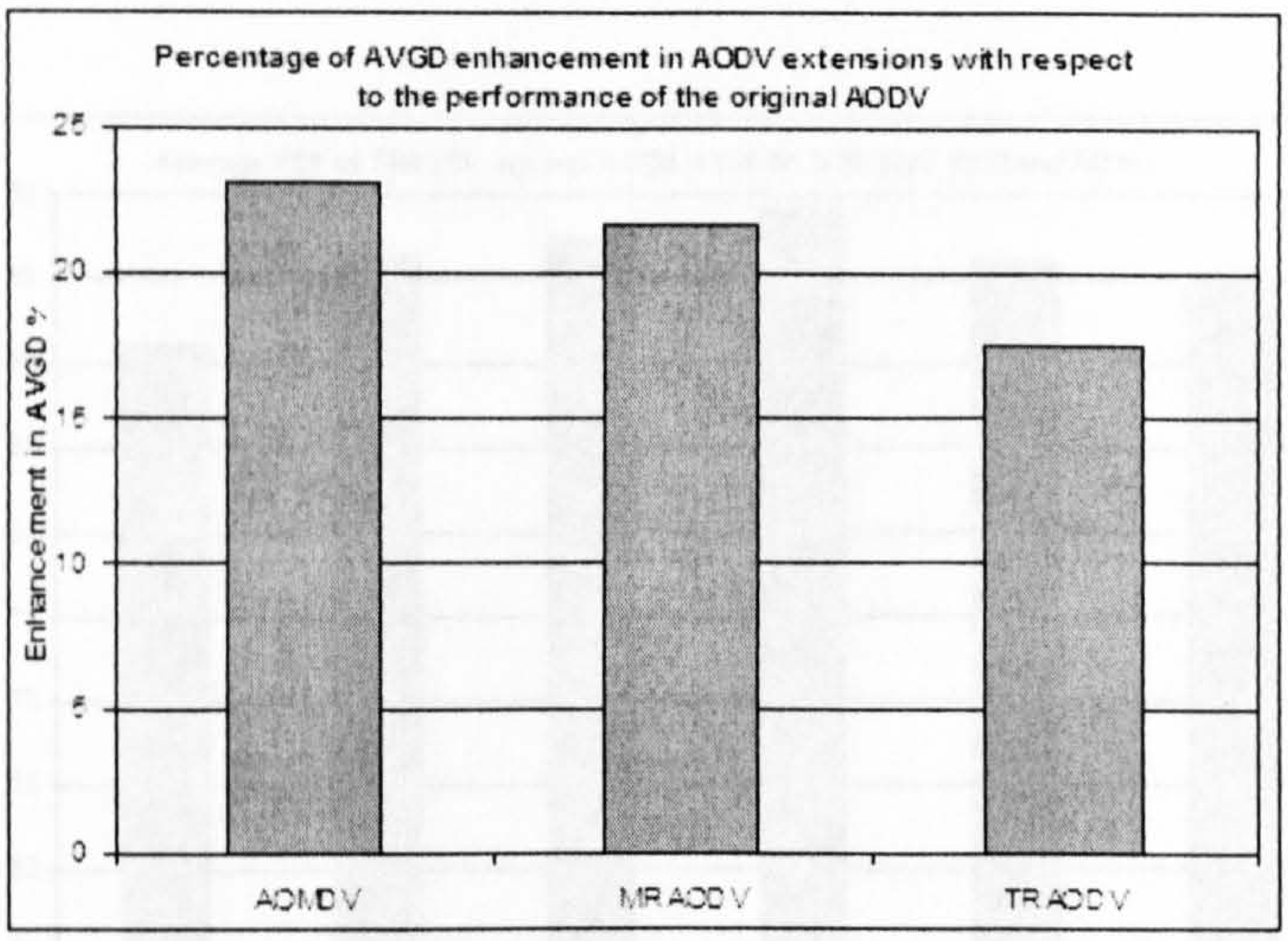

Figure 7.23: AVGD in TRAODV compared to AOMDV and MRAODV

The reason of the worse performance of TRAODV in terms of the average end-to-end delay compared to MRAODV, especially in high mobility scenarios is that both protocols invoke a new RDP when a broken link is detected. As MRAODV has so many inefficient routes in its routing table, it detects the need to reinvoke a RDP earlier than TRAODV. Before invoking a new RDP, TRAODV first tries to utilise all efficient routes in the table. Because of the high mobility, an efficient route that is utilised for data transmission may fail after a short time, which leads to reinvoke a new RDP with some delay. This delay is considered more overhead on the average end-to-end delay of the whole routing process. Using a local repair procedure for link failures instead of reinvoke a new RDP is a solution for this problem. This solution is applied later in ORMAD approach (the second novel approach of this thesis) which concerns the phase of route maintenance in multipath AODV. Furthermore, a fuzzy logic model may be useful to detect the number of efficient routes that are exactly needed, which may reduce the delay overhead of TRAODV. This solution is suggested in the Chapter 8 as a future work of this research.

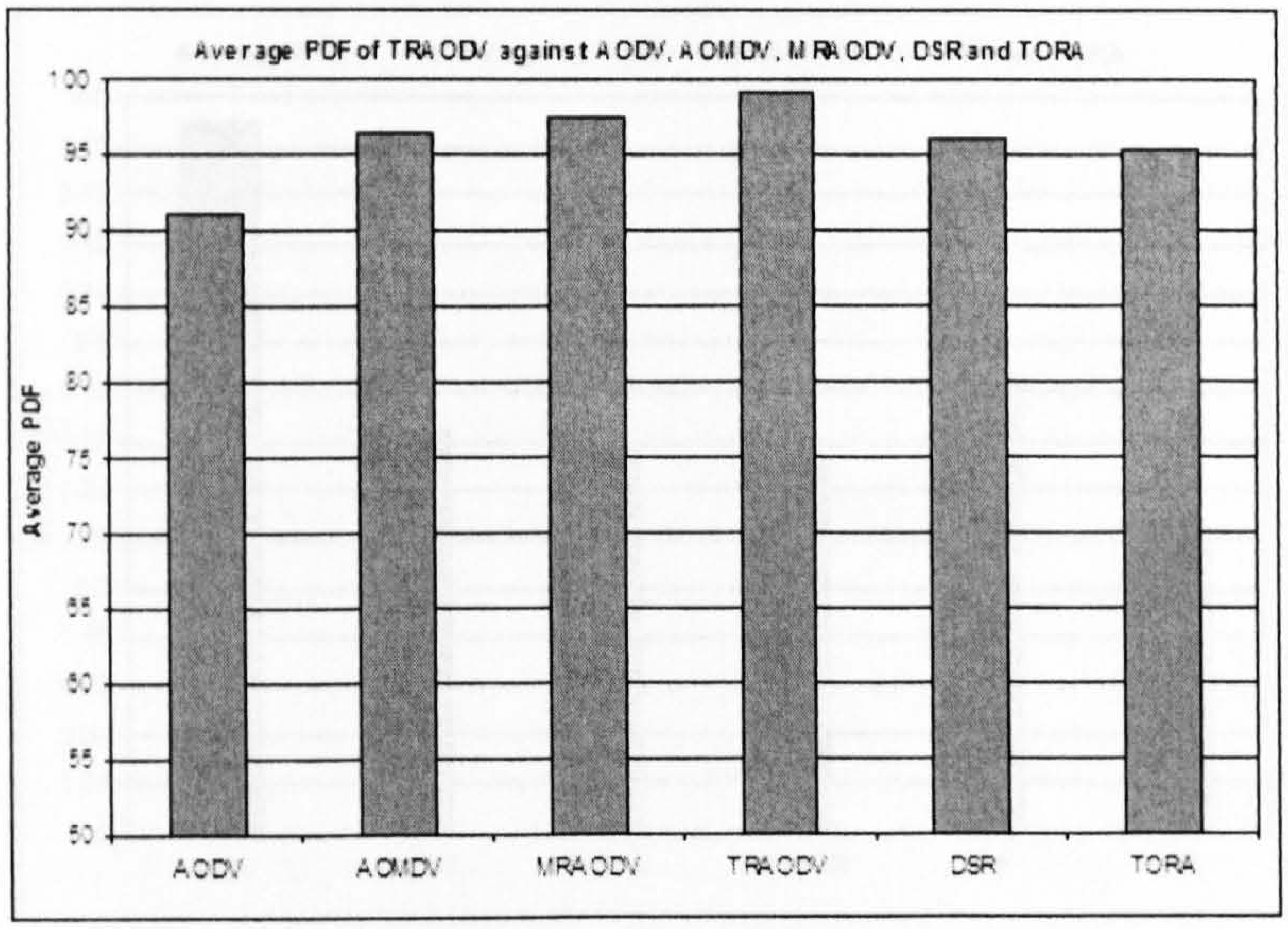

Figure 7.24: Average PDF in TRAODV compared to AODV extensions and traditional multipath protocols

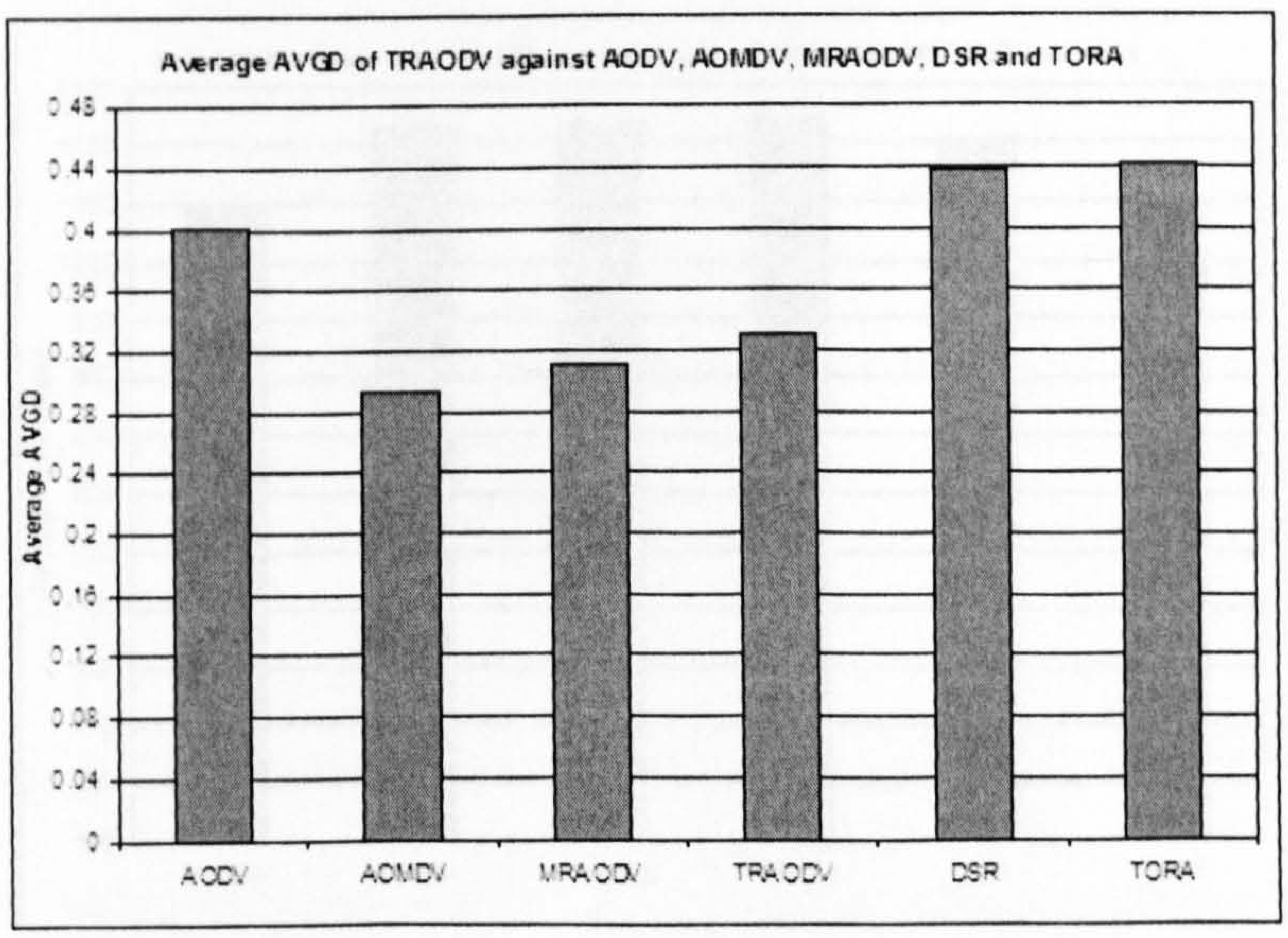

Figure 7.25: Average AVGD in TRAODV compared to AODV extensions and traditional multipath protocols

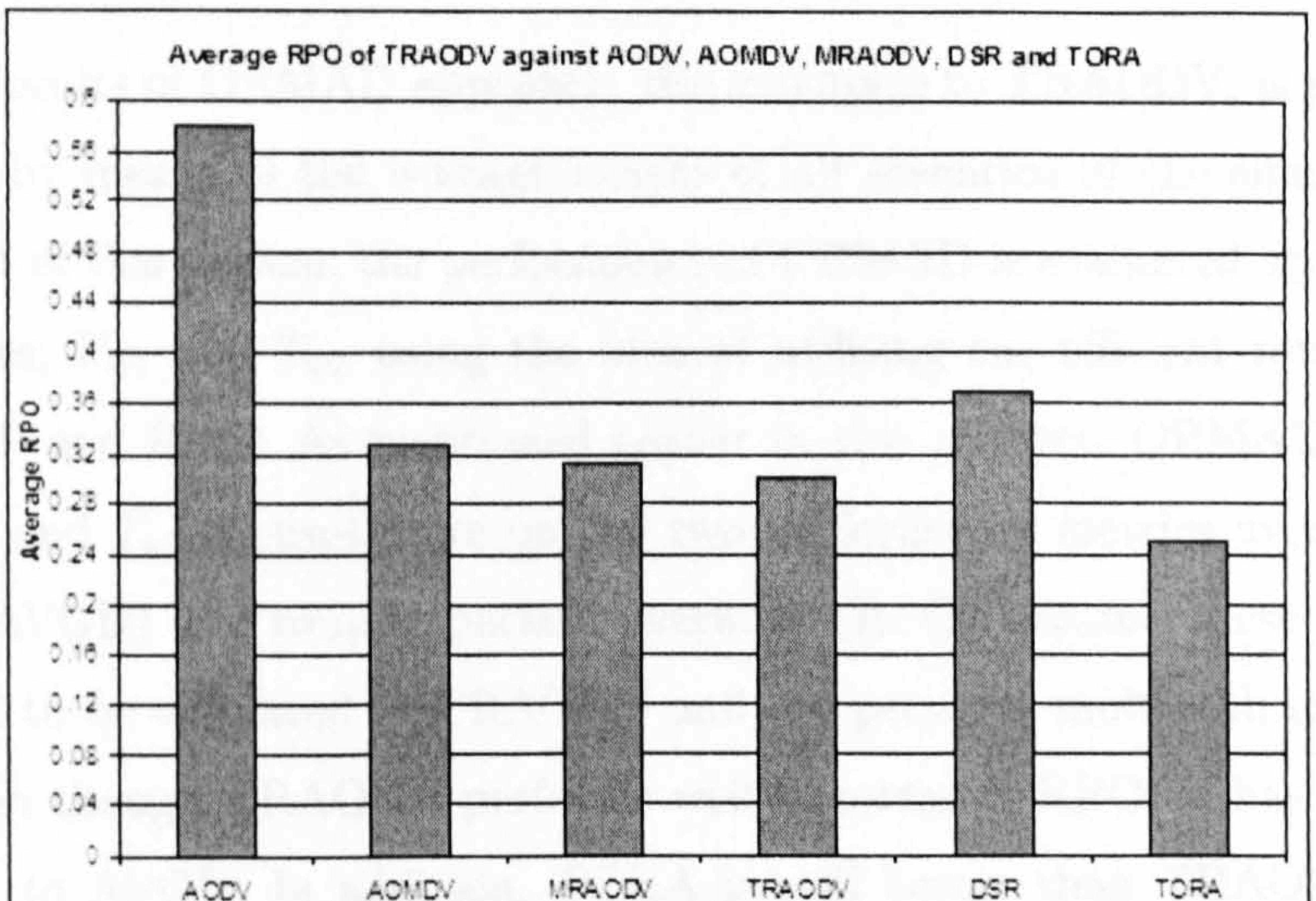

Figure 7.26: Average RPO in TRAODV compared to AODV extensions and traditional multipath protocols

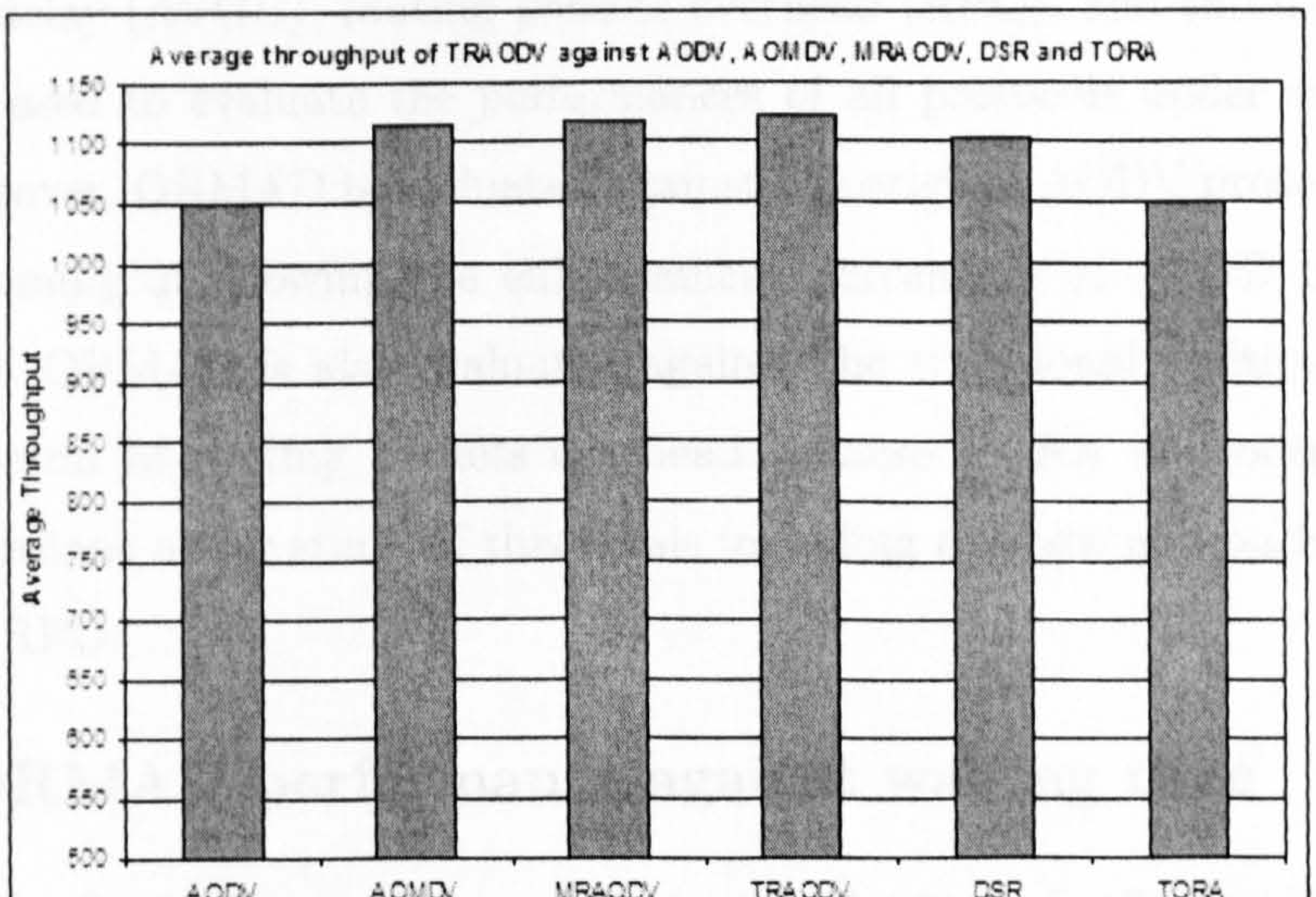

Figure 7.27: Average throughput in TRAODV compared to AODV extensions and traditional multipath protocols

7.3 Results Study of ORMAD Simulation

Simulation results of ORMAD approach, the extension to TRAODV, is presented in this section by means of the average results of all scenarios of the simulations. In the first part of this section, the performance of ORMAD is evaluated against RREP waiting times; T_{w1} and T_{w2} using the idea of utilising the efficient routes in both phases; RDP and RMP. As mentioned earlier in this chapter, ORMAD evaluation against T_{w1} and T_{w2} focuses more on the two performance metrics average end-to-end delay (AVGD) and routing packets overhead (RPO) because these two metrics are targeted to be enhanced in TRAODV and the previous multipath extensions to AODV. Even though TRAODV performs well in terms of RPO, it has a drawback with regard to AVGD. In addition, TORA is still better than TRAODV and the other extensions to AODV which are under study in this thesis in terms of RPO.

In the second part of this section, the performance of ORMAD is evaluated against TRAODV and the other multipath extensions to AODV, namely MRAODV and AOMDV in terms of the performance metrics; packet delivery fraction (PDF), average end-to-end delay (AVGD), routing packets overhead (RPO), and throughput which are usually used to evaluate the performances of all protocols under study in this thesis. Moreover, ORMAD is evaluated against the original AODV protocol in terms of AVGD aiming at showing the enhancement percentage of AVGD from AODV to ORMAD. ORMAD is also evaluated against the traditional multipath protocol TORA in terms of routing packets overhead because TORA still outperforms all AODV extensions under study of this thesis including our new approach, TRAODV in terms of RPO.

7.3.1 ORMAD performance against waiting time

In TRAODV, simulation results prove that using the idea of utilising efficient routes and threshold waiting time in RREPs of route discovery process (RDP) improves the performance of multipath extensions to AODV compared to traditional multipath protocols; DSR and TORA in terms of the four performance metrics; PDF, AVGD, RPO, and throughput. The same idea is applied in ORMAD but for the two phases RDP and RMP by varying two time variables; T_{w1} and T_{w2} for RDP and RMP respectively. Simulation results of ORMAD show that the performance is affected by varying T_{w1} and T_{w2} in different scenarios.

As shown by Figure 7.28, the performance of ORMAD in terms of RPO improves toward the threshold point (T_{w1}=8s and T_{w1}=3s) where RPO reaches the best case (RPO=0.2865). As shown by the figure, the performance reduces by moving to the ends of T_{w1}; 1s and 20s. The worst case is 0.3112 which is reached at the point T_{w1}=20s and T_{w1}=5s. Figure 7.29 shows the average RPO in ORMAD for each waiting time of RMP; T_{w2}=1, 3, and 5 seconds. As shown by the figure, the best average performance is achieved at T_{w2}=3s regardless of the value of T_{w1}. However, the optimal value of RPO is reached at the intersection point T_{w2}=3s with T_{w1}=8s which is illustrated by Figure 7.28.

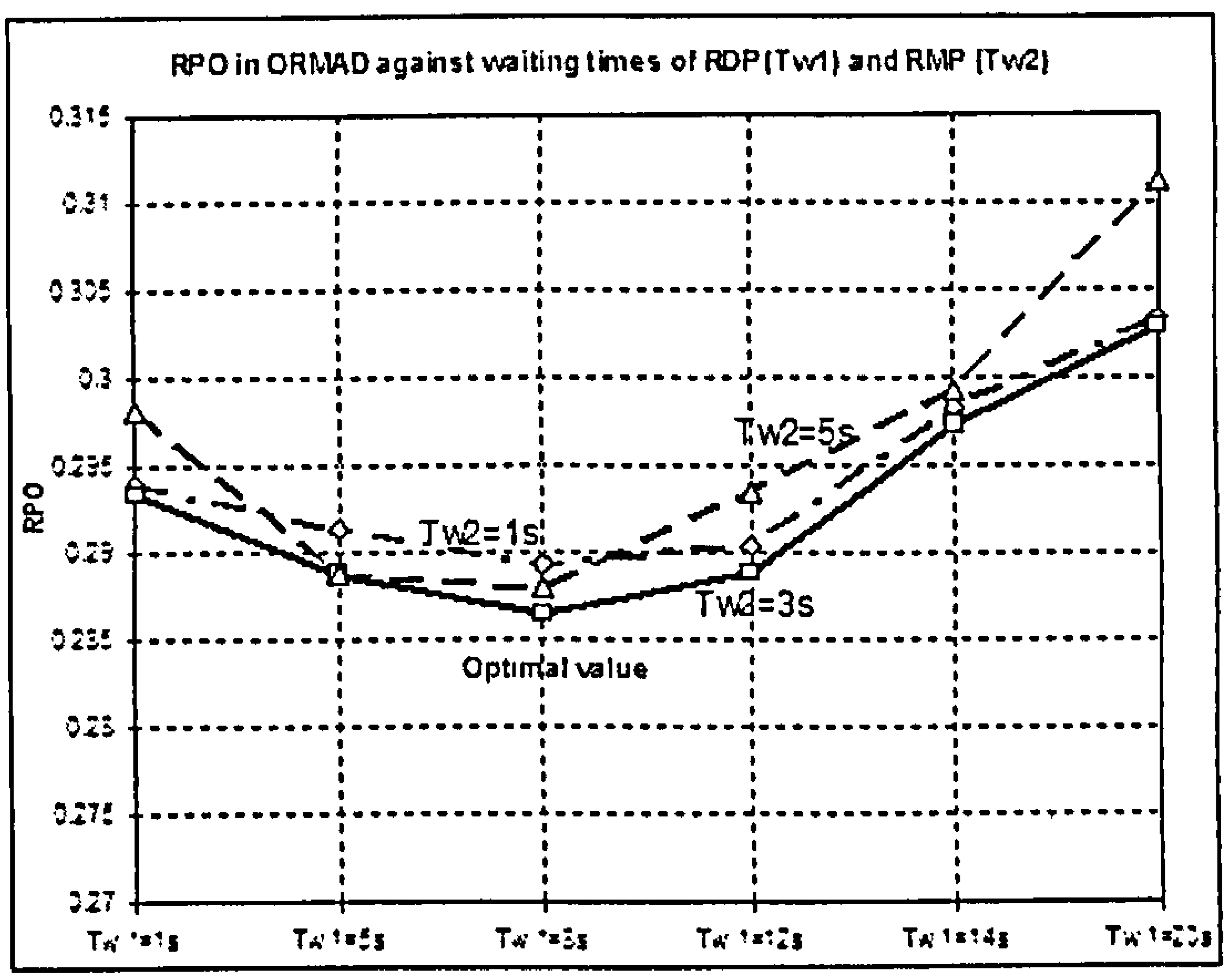

Figure 7.28: RPO in ORMAD against waiting times of RDP (Tw1) and RMP (Tw2)

As shown by Figure 7.30, the performance of ORMAD in terms of AVGD improves

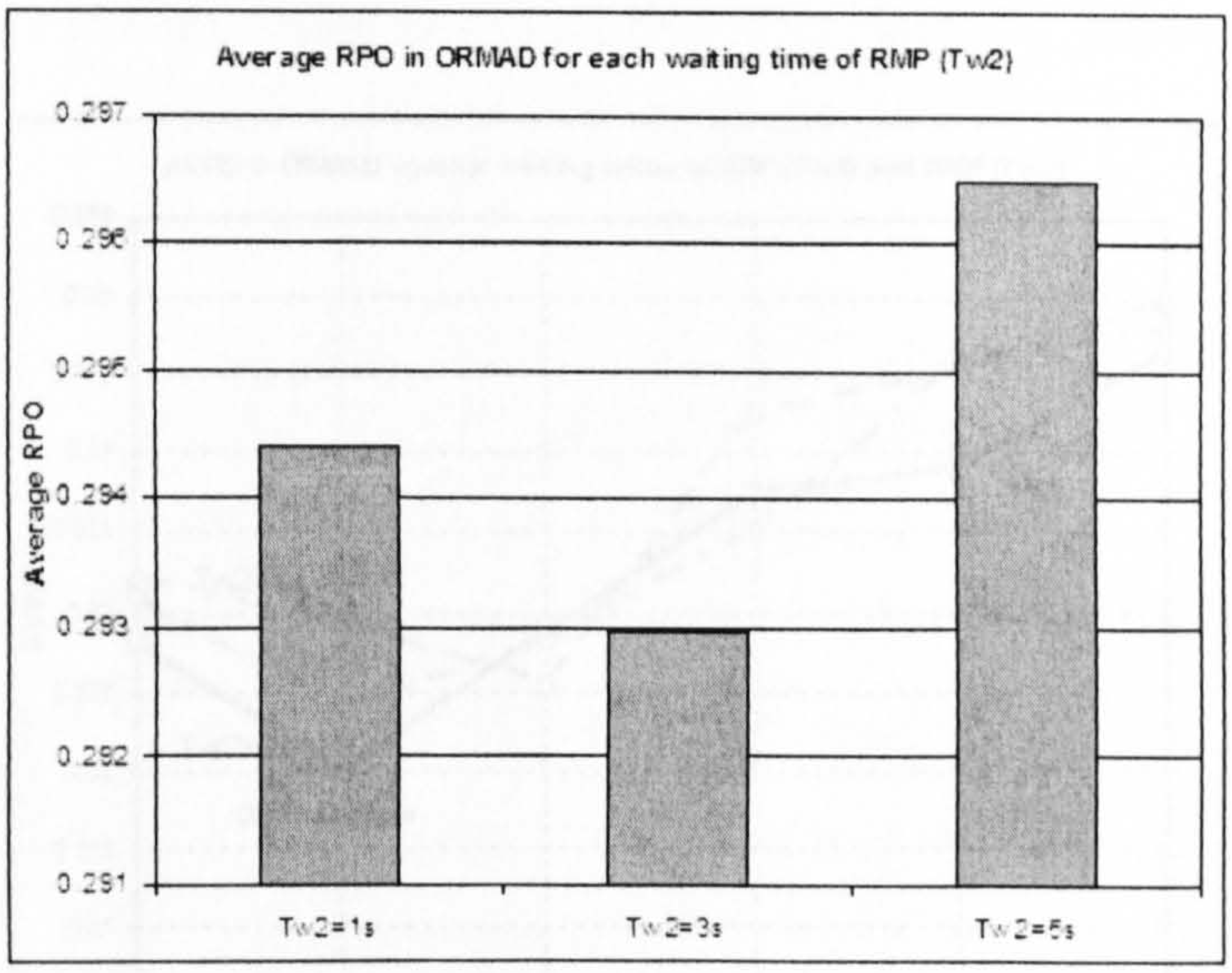

Figure 7.29: Average RPO in ORMAD for each waiting time of RMP (T_{w2})

toward the threshold point (T_{w1}=5s and T_{w1}=3s) where AVGD reaches the best case (AVGD=0.320077). As shown by the figure, the performance reduces by moving to the upper end of T_{w1} (20s) more than to the upper end of T_{w1} (1s). The worst case is 0.3375482 which is reached at the point T_{w1}=20s and T_{w1}=5s. Figure 7.31 shows the average AVGD in ORMAD for each waiting time of RMP; T_{w2}=1, 3, and 5 seconds. As shown by the figure, the best average performance is achieved at T_{w2}=3s regardless of the value of T_{w1}. However, the optimal value of AVGD is reached at the intersection point T_{w2}=3s with T_{w1}=5s which is illustrated by Figure 7.30.

7.3.2 ORMAD evaluation against the other extensions

Figure 7.32 illustrates a comparison of ORMAD performance against TRAODV, MRAODV, and AOMDV in terms of PDF by which the simulation results show that ORMAD outperforms TRAODV, MRAODV, and AOMDV, especially in high mobility scenarios. As shown in the figure, the performance of ORMAD converges to the performance of TRAODV and MRAODV in low mobility scenarios. AOMDV has the worst performance in terms of PDF in high mobility scenarios however, it converges to the performance of MRAODV in low mobility scenarios. As shown in

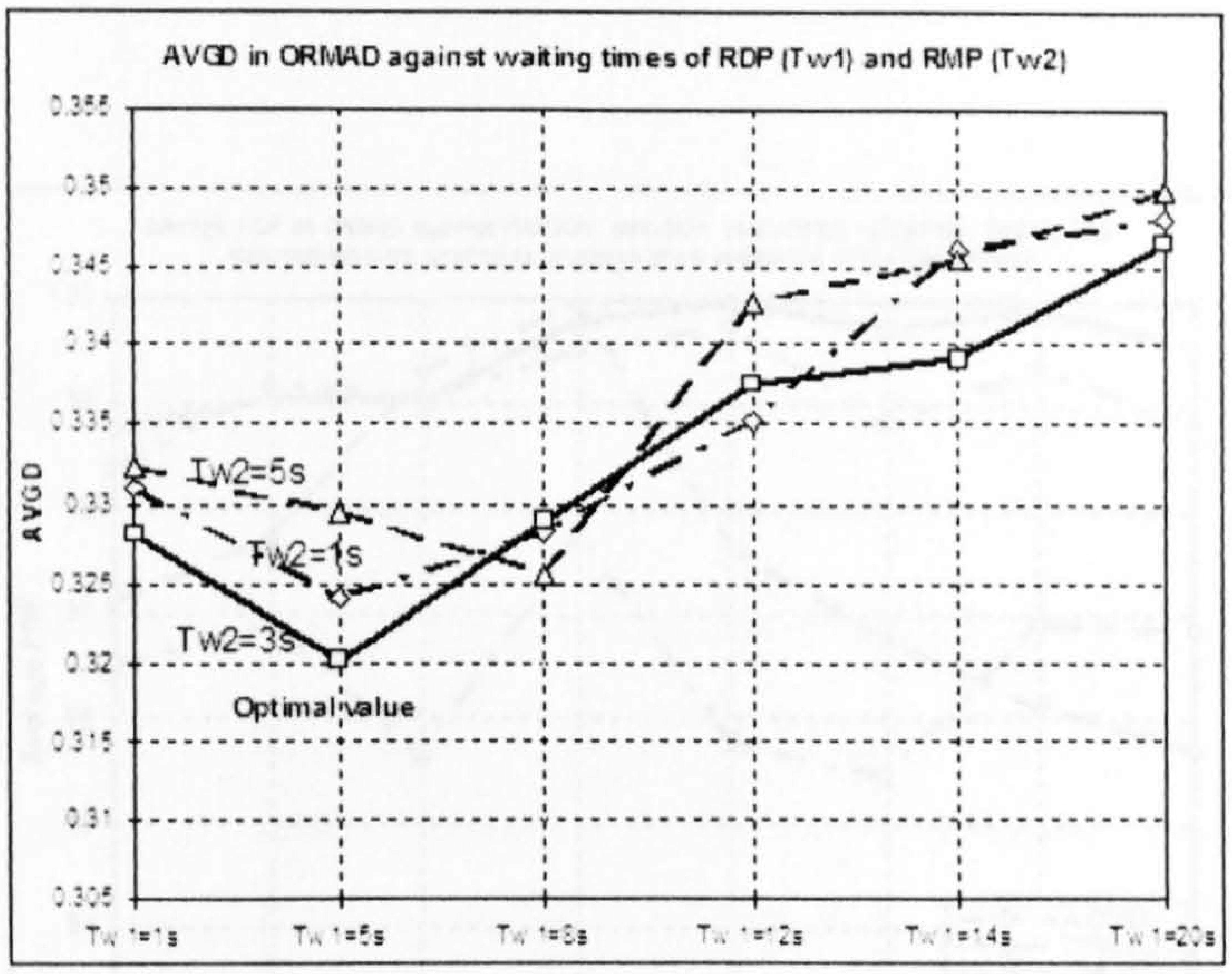

Figure 7.30: AVGD in ORMAD against waiting times of RDP (T_{w1}) and RMP (T_{w2})

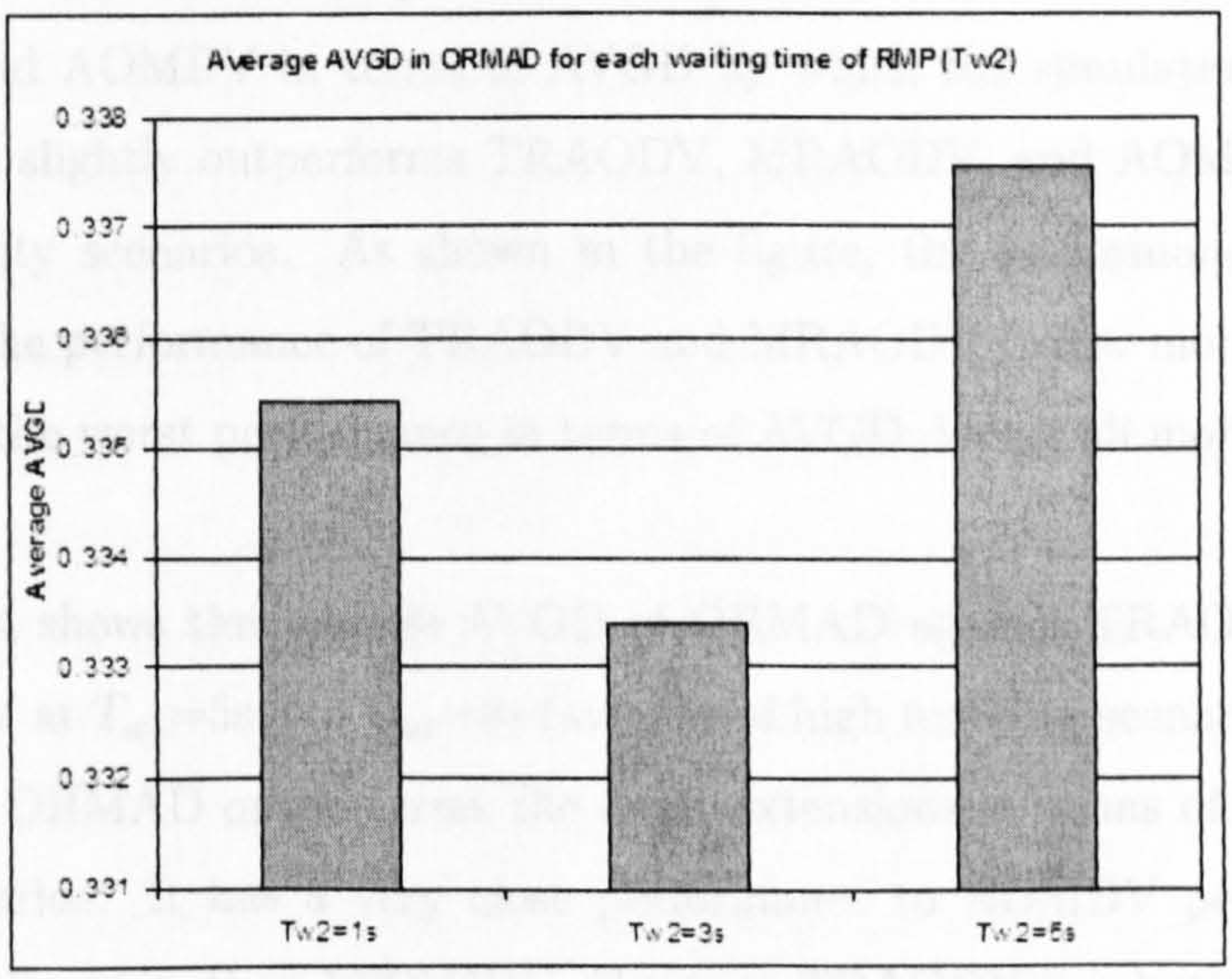

Figure 7.31: Average AVGD in ORMAD for each waiting time of RMP (T_{w2})

the figure, ORMAD and TRAODV performs better than the others in low mobility scenarios.

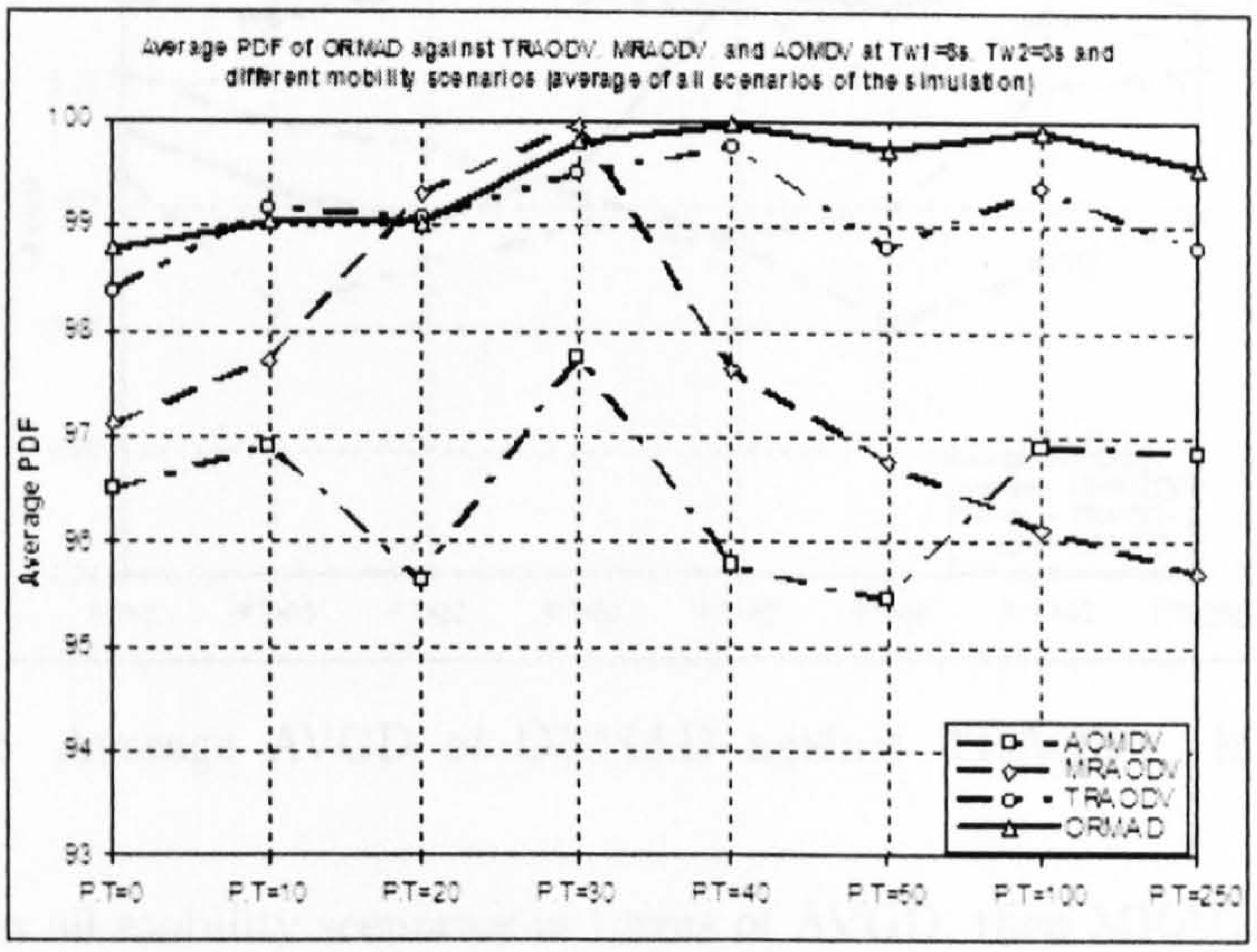

Figure 7.32: Average PDF of ORMAD against TRAODV, MRAODV, and AOMDV

Figure 7.33 illustrates a comparison of ORMAD performance against TRAODV, MRAODV, and AOMDV in terms of AVGD by which the simulation results show that ORMAD slightly outperforms TRAODV, MRAODV, and AOMDV, especially in high mobility scenarios. As shown in the figure, the performance of ORMAD converges to the performance of TRAODV and MRAODV in low mobility scenarios. AOMDV has the worst performance in terms of AVGD during all mobility scenarios.

Figure 7.34 shows the average AVGD of ORMAD against TRAODV, AOMDV, and MRAODV at T_{w1}=5s and T_{w2}=3s (average of high mobility scenarios). As shown by the figure, ORMAD outperforms the other extensions in terms of AVGD in high mobility scenarios. It has a very close performance to AOMDV performance and TRAODV is the next, then MRAODV. However TRAODV has better performance than MRAODV and ORMAD respectively in low mobility scenarios which is shown by Figure 7.35. As a general performance which is shown by Figure 7.36 , AOMDV is

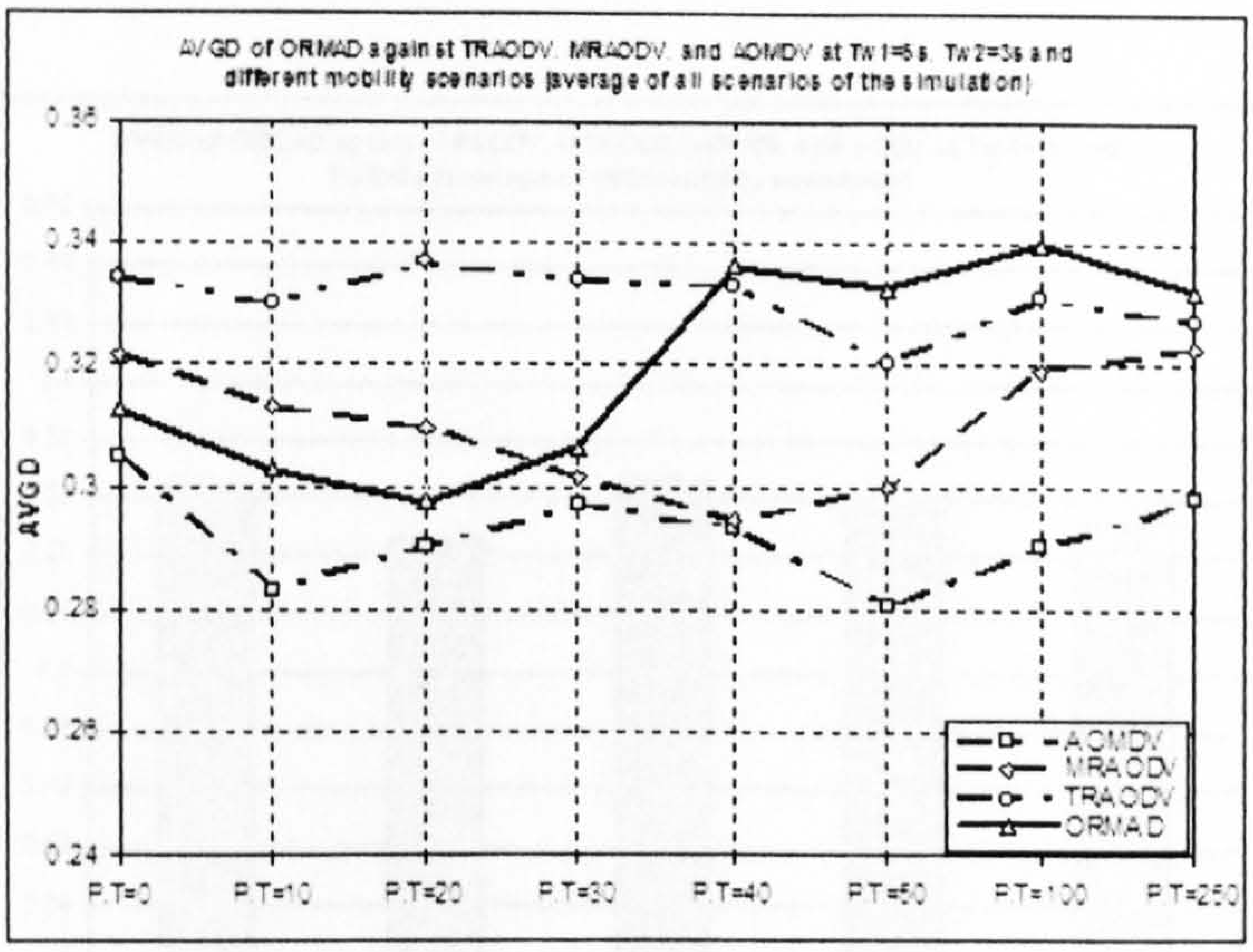

Figure 7.33: Average AVGD of ORMAD against TRAODV, MRAODV, and AOMDV

still the best in all mobility scenarios in terms of AVGD, then MRAODV, ORMAD, and finally TRAODV which has the worst general performance.

Figure 7.37 illustrates a comparison of ORMAD against TRAODV, TRAODV, MRAODV, and AOMDV in terms of routing packet overhead. As shown by the figure, ORMAD outperforms the other extensions in terms of RPO in all mobility scenarios and especially in high scenarios. Figure 7.38 shows that ORMAD has the closest performance to TORA performance, then MRAODV, TRAODV, and AOMDV respectively. As shown by Figures 7.39 and 7.40 ORMAD also still has the best performance in terms of RPO in medium scenarios and even in the average performance of all mobility scenarios. However, the traditional multipath protocol TORA is still the best in terms of RPO with a slight difference from ORMAD.

Figure 7.41 illustrates a comparison of ORMAD performance against TRAODV, MRAODV, and AOMDV in terms of throughput by which the simulation results show that ORMAD outperforms TRAODV, MRAODV, and AOMDV, especially in high

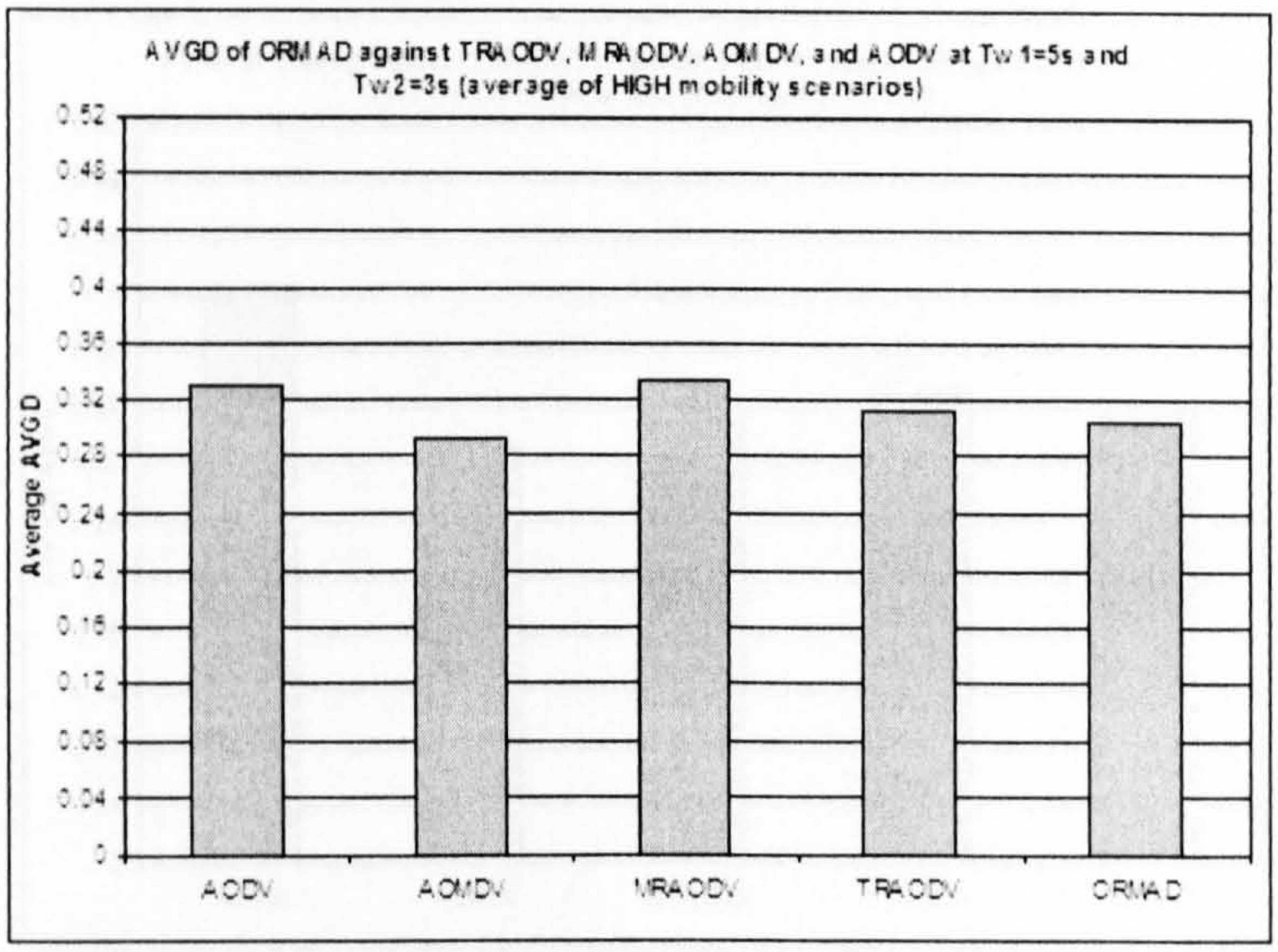

Figure 7.34: Average of AVGD in ORMAD against all protocols (high mobility scenarios)

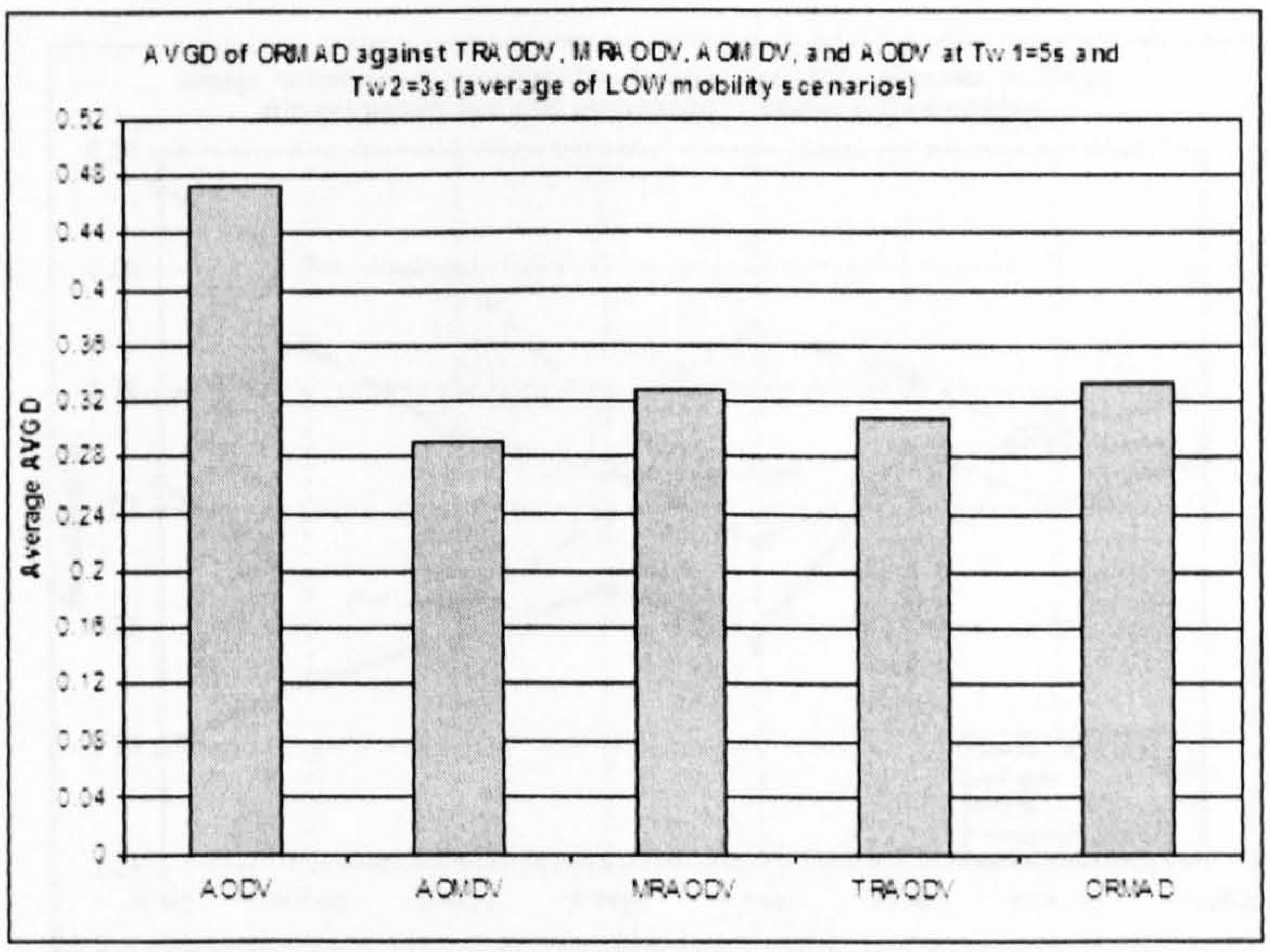

Figure 7.35: Average of AVGD in ORMAD against all protocols (low mobility scenarios)

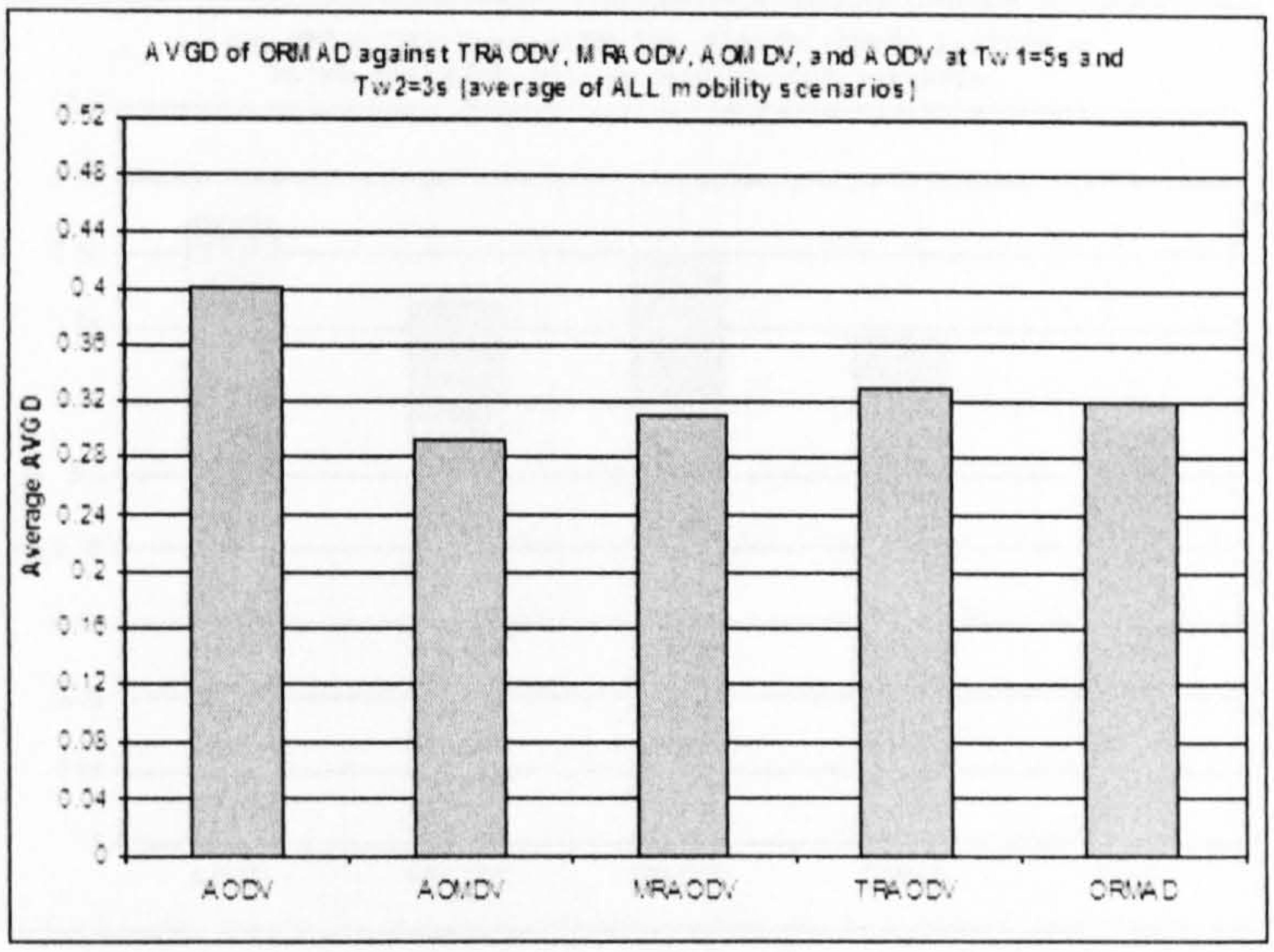

Figure 7.36: Average of AVGD in ORMAD against all protocols (all mobility scenarios)

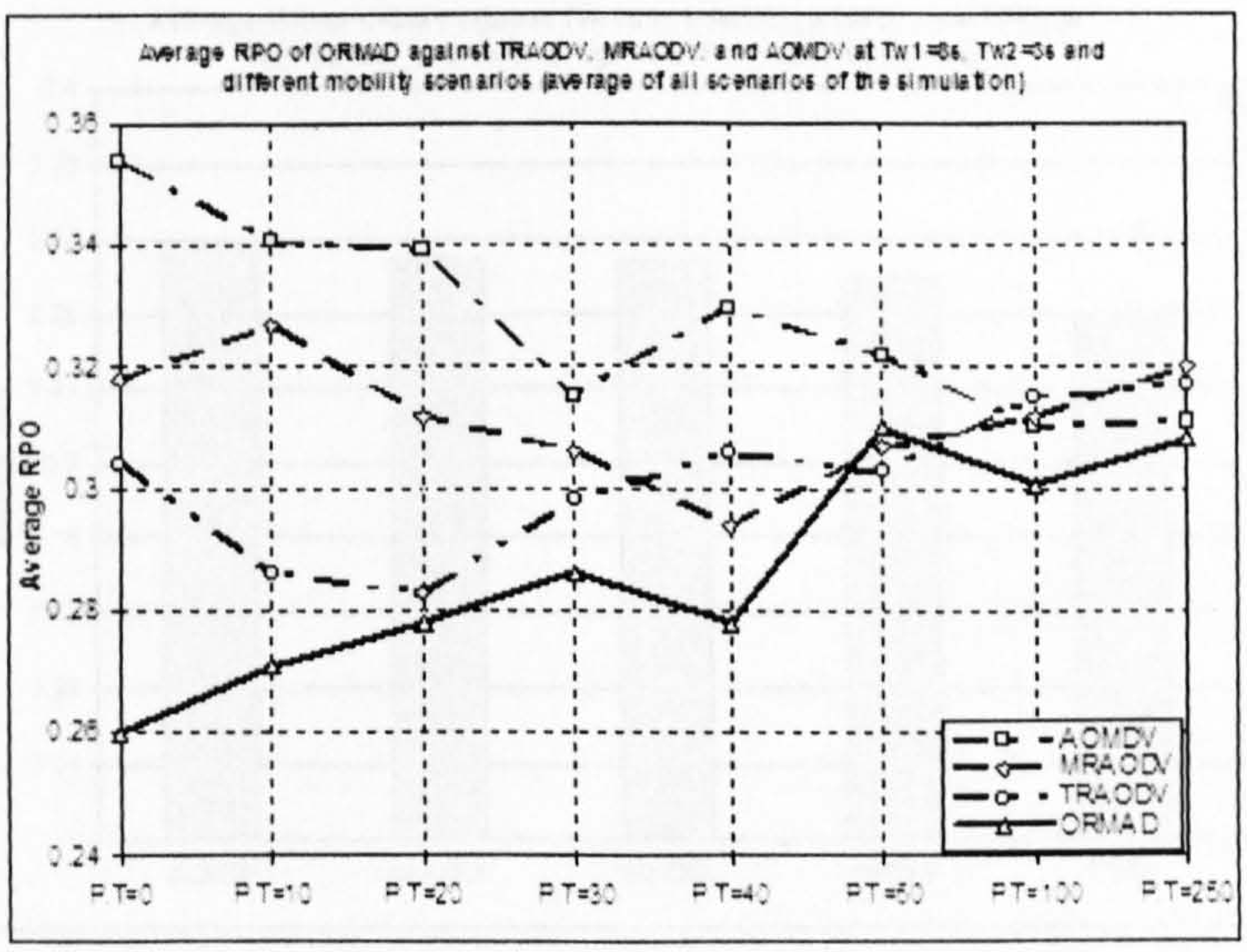

Figure 7.37: Average RPO of ORMAD against TRAODV, TRAODV, MRAODV, and AOMDV

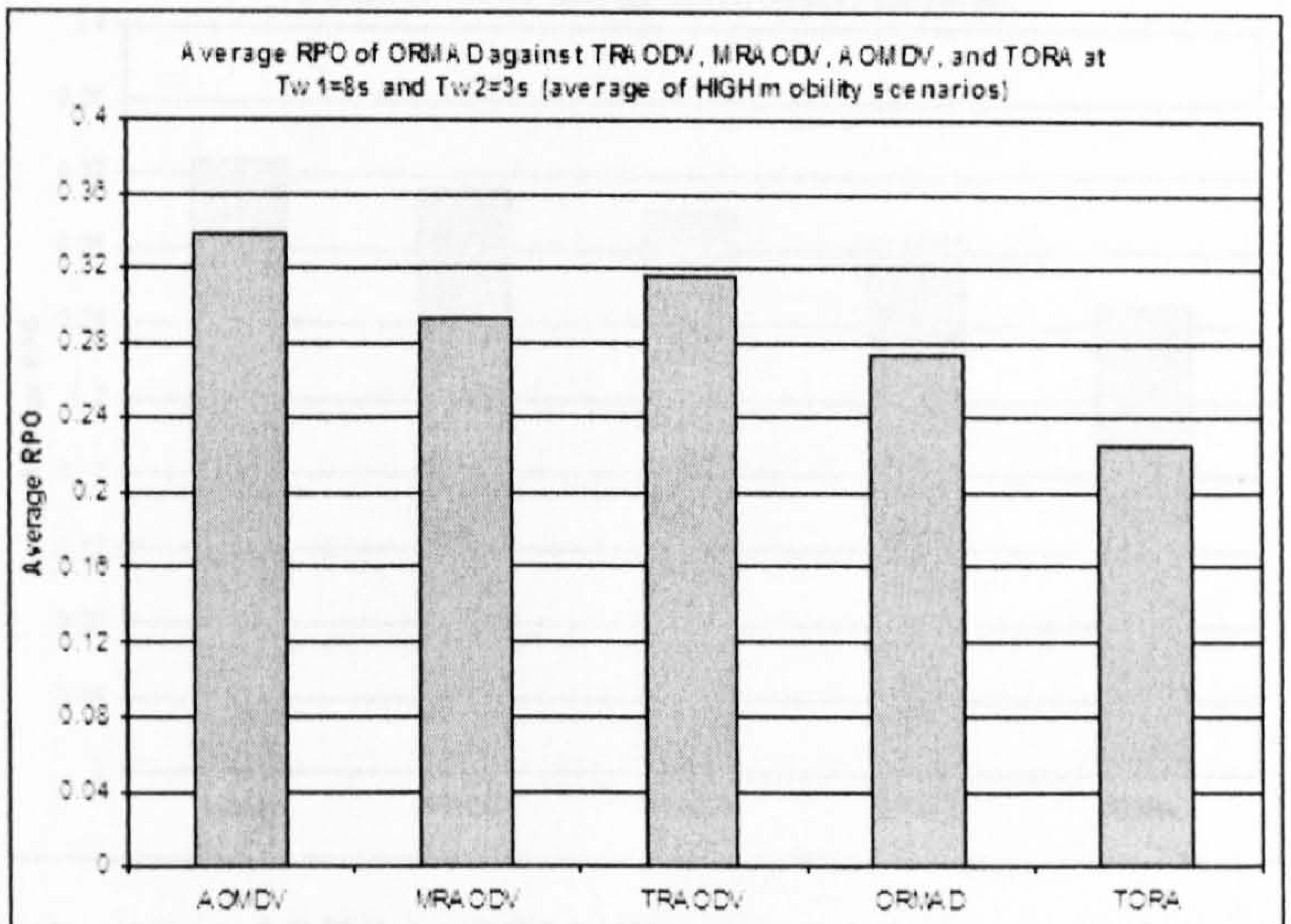

Figure 7.38: Average of RPO in ORMAD against all protocols (high mobility scenarios)

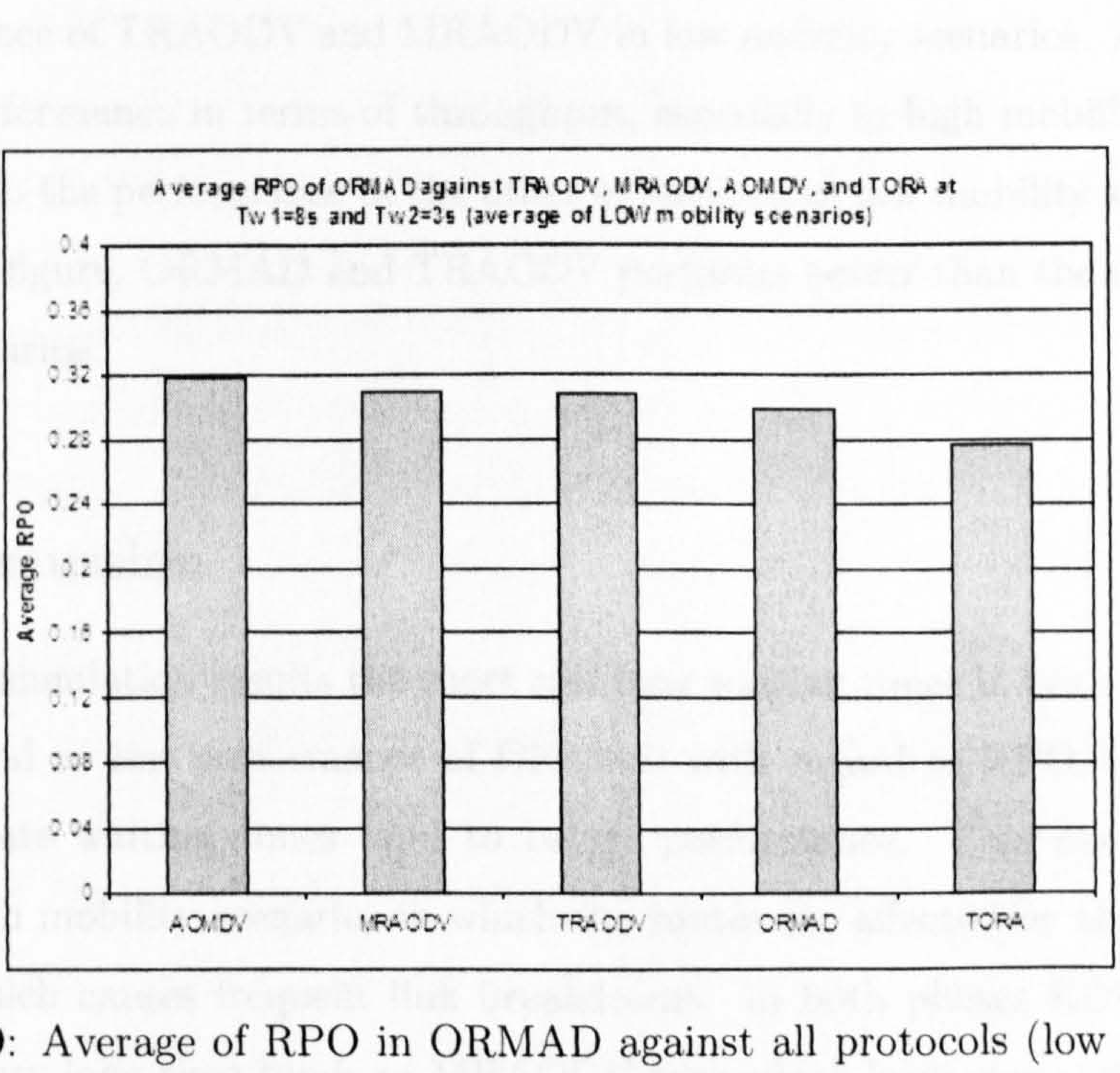

Figure 7.39: Average of RPO in ORMAD against all protocols (low mobility scenarios)

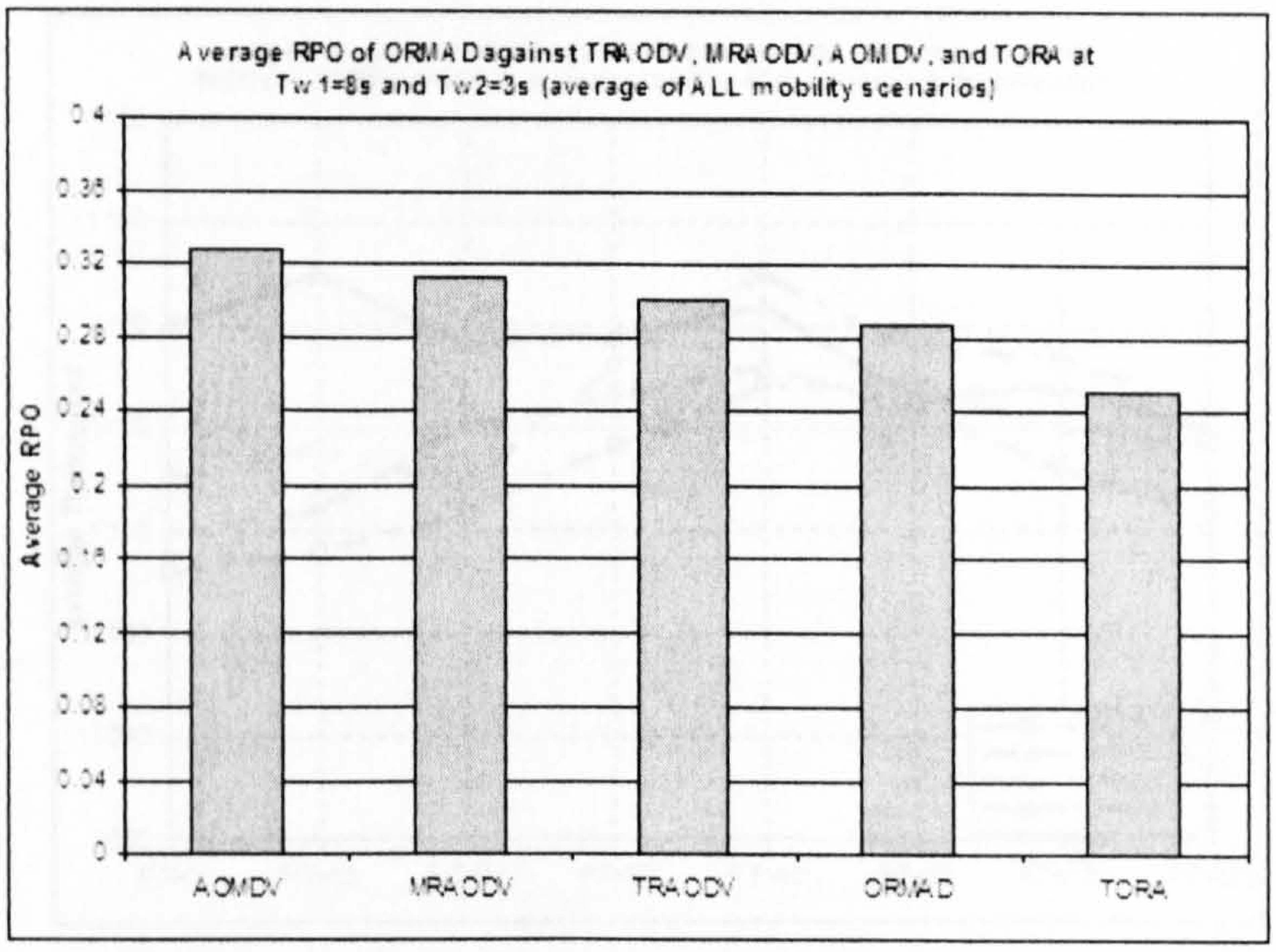

Figure 7.40: Average of RPO in ORMAD against all protocols (all mobility scenarios)

mobility scenarios. As shown in the figure, the performance of ORMAD converges to the performance of TRAODV and MRAODV in low mobility scenarios. AOMDV has the worst performance in terms of throughput, especially in high mobility scenarios. It converges to the performance of the other extensions at low mobility scenarios. As shown in the figure, ORMAD and TRAODV performs better than the others in low mobility scenarios.

7.3.3 Discussion

As shown by simulation results the short and long waiting times in both phases RDP and RMP tend to less performance of ORMAD with regard to RPO. On the other hand, moderate waiting times tend to better performance. This can be justified mainly in high mobility scenarios in which the routes are affected by the mobility of the nodes which causes frequent link breakdowns. In both phases RDP and RMP, waiting for very long time tends to MRAODV case which loses more efficient routes stored in the routing table which get broken down. Despite the fact that ORMAD

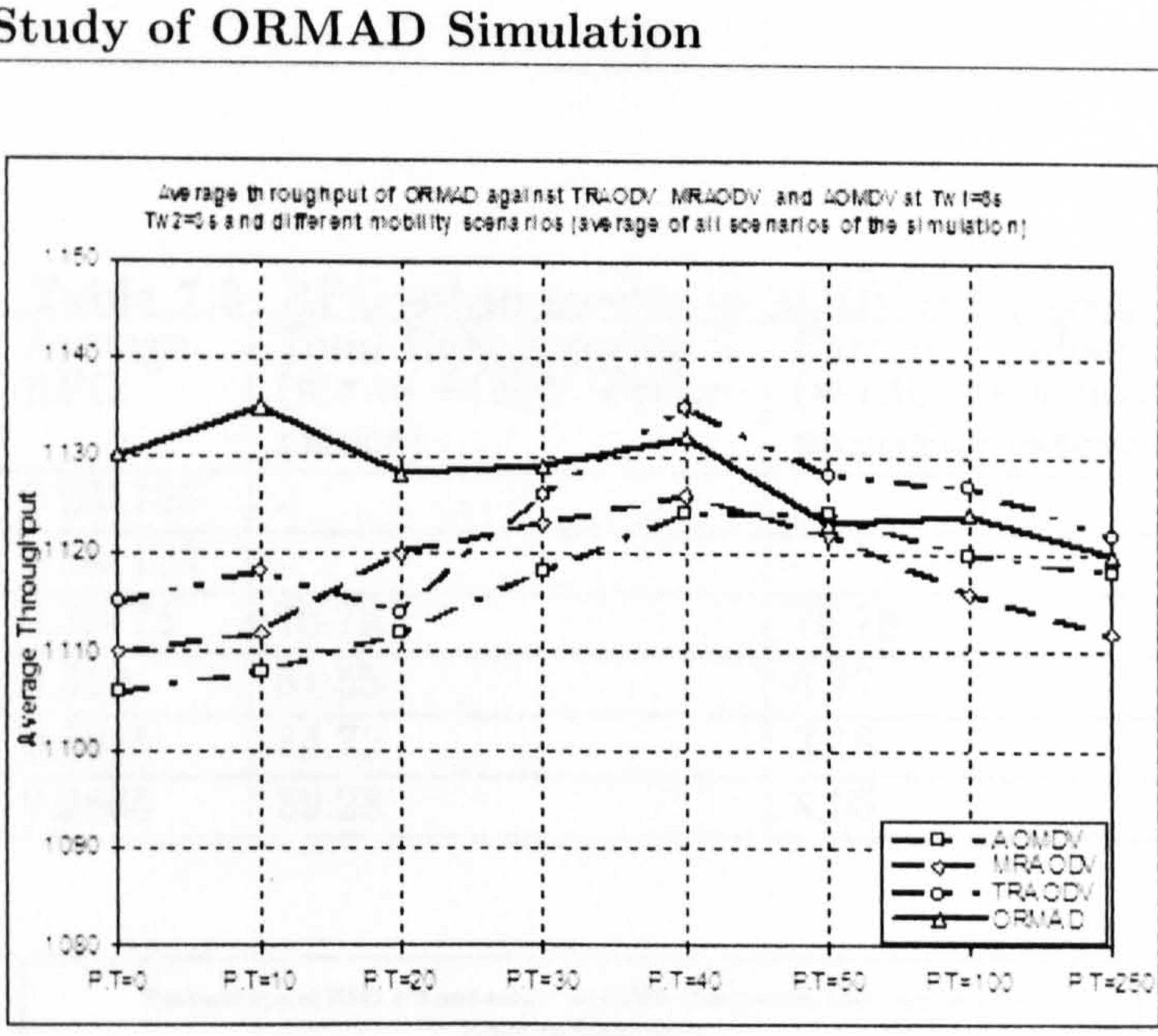

Figure 7.41: Average throughput of ORMAD against TRAODV, TRAODV, MRAODV, and AOMDV

tries to repair the broken efficient routes as needed (on-demand), the long waiting time in RMP may cause other failures in the other routes or in the other valid links of the route under repairing. Also, applying very short durations of waiting time in RDP leads to AOMDV case which detect a very few number of routes. Similarly, it leads to less number of efficient subroutes while repairing a failed primary route. For these reasons, applying moderate waiting times are recommended for both RDP and RMP to improve ORMAD performance in terms of RPO, and this is also true for PDF and throughput which have the optimal values at the same threshold point of RPO. However, the performance with regard to AVGD has different behaviour which is described later in this section.

Table 7.3 and its representation in Figure 7.42 shows the percentage of RPO enhancement in AODV extensions with respect to the performance of TORA. As shown by the figure, ORMAD enhances the performance of TRAODV in terms of RPO performance metric, it has the best performance (and the closest to TORA performance) amongst all multipath extensions to AODV which are under study in this thesis, and this is a significant advantage of ORMAD approach.

Table 7.3: RPO enhancements in AODV extensions

Protocol	Average RPO	Total Enhancement % (w.r.to AODV Performance)	Partial Enhancement % (w.r.to Performance of the preceding extension)
TORA	0.251125	-	-
AODV	0.581125	-	-
AOMDV	0.32775	76.78	76.78
MRAODV	0.312	81.55	4.77
TRAODV	0.3015	84.73	3.18
ORMAD	0.2865	89.28	4.55

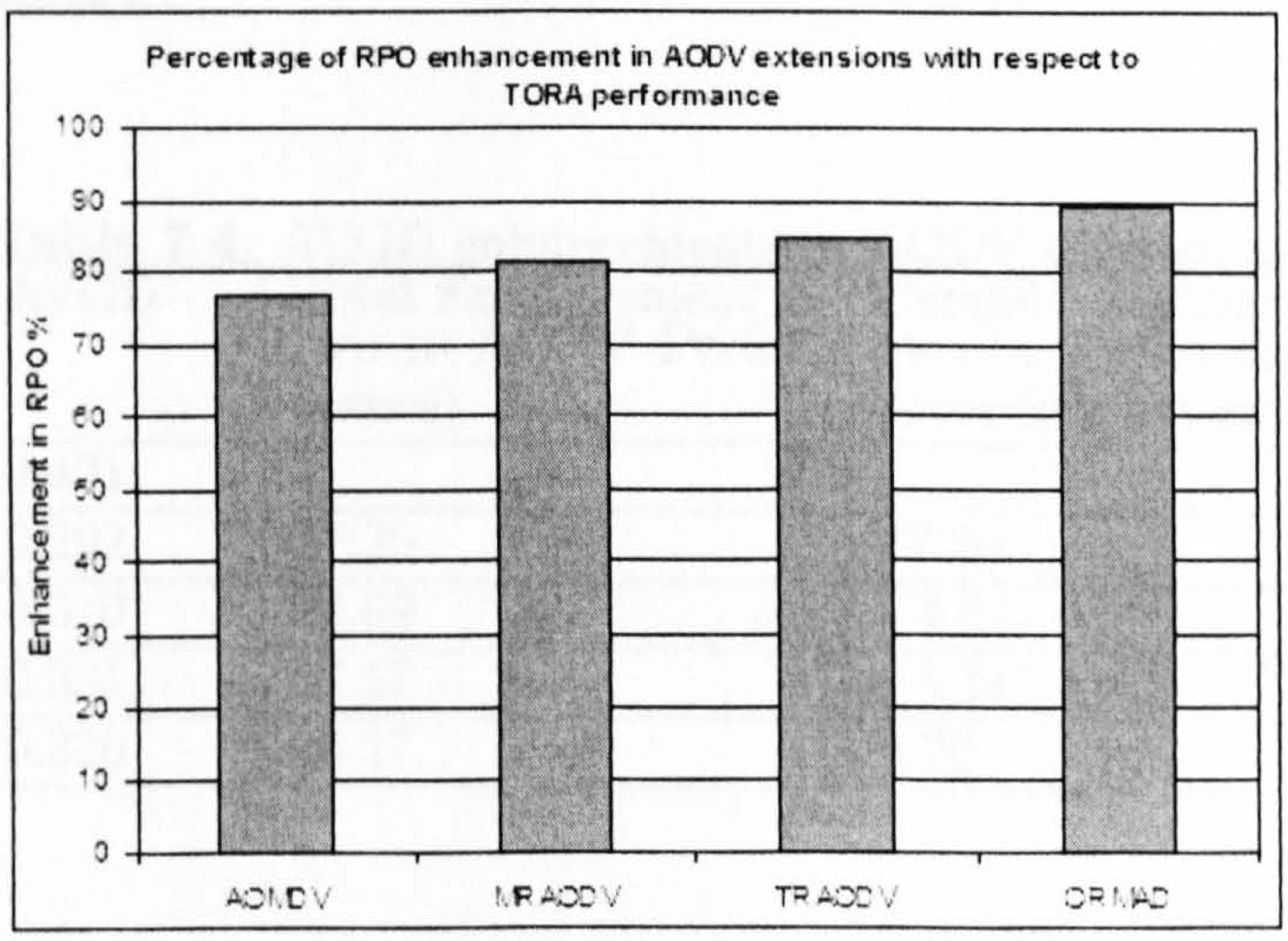

Figure 7.42: Percentage of RPO enhancement in AODV extensions with respect to the performance of TORA

The case of AVGD is similar to RPO case with regard to the waiting time of both phases RDP and RMP. Moderate times still tend to better performance in terms of AVGD and the justification mentioned above for RPO case is still valid for AVGD case. However, the threshold point of AVGD is different so that the waiting time of RDP is moved to T_{w1}=5s while T_{w2} is fixed at 3 seconds. This can be justified by the overhead of the waiting time on the average end-to-end delay of the routing process. The lower the waiting time the lower the delay overhead but not absolutely because waiting for very short time leads to detect a very few number of routes which leads to the case of AOMDV and sometimes to the behaviour of the single path protocol AODV. Hence, the threshold point of the optimal AVGD is reasonable in ORMAD performance.

Table 7.4 and its representation in Figure 7.43 shows the percentage of AVGD enhancement in AODV extensions with respect to the performance of the original AODV. As shown in the figure, ORMAD has a good performance in high mobility scenarios in terms of AVGD so that it tries to balance the reduction in TRAODV performance by applying the local repairing process on the efficient routes and extending the waiting time to RREPs in RMP, and this is another significant advantage of ORMAD approach.

Table 7.4: AVGD enhancements in AODV extensions

Protocol	AVGD	Total Enhancement % (w.r.to AODV Performance)	Partial Enhancement % (w.r.to Performance of the preceding extension)
AODV	0.401	-	-
AOMDV	0.292	27.20	27.20
MRAODV	0.310	22.69	- 4.51
TRAODV	0.331	17.57	- 5.11
ORMAD	0.320	20.27	2.70

7.4 Testing and Evaluation of the Analytical Model of ORMAD

In this section, an analytical study is achieved numerically for the analytical Model of ORMAD by implementing the analytical model developed in Chapter 6 and running it on 6561 records of testing data using Matlab 6.0. Firstly, Equation (6.35) is implemented and run on the testing data to study the rate of change of multipath degree λ with respect to the mobility ratio μ. Secondly, Equation (6.12) is implemented and run on the testing data to study the behaviour of the total number of routes (M_t) in terms of three input parameters connectivity, mobility and waiting time ratios.

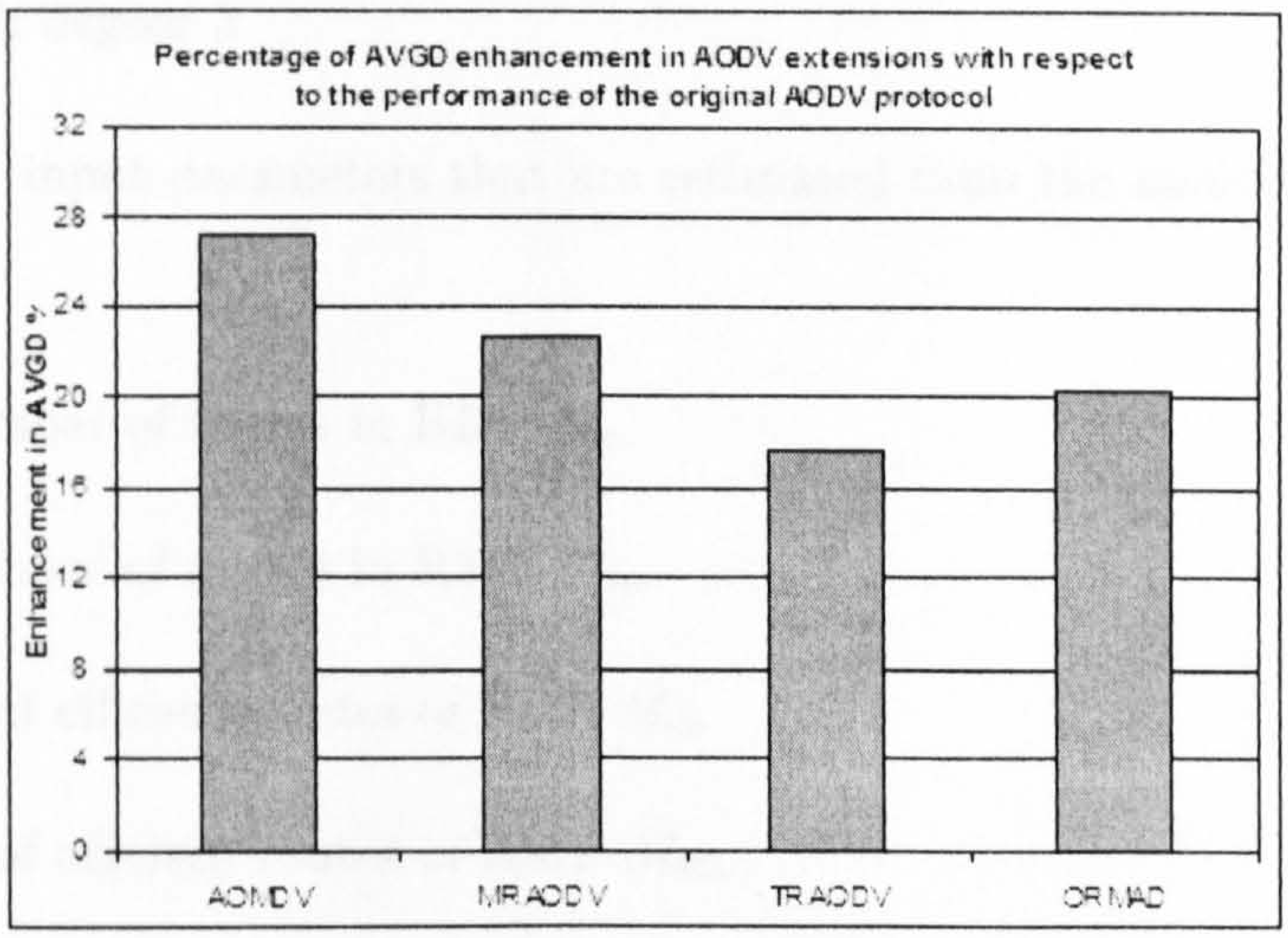

Figure 7.43: Percentage of AVGD enhancement in AODV extensions with respect to the performance of the original AODV

Thirdly, Equation (6.27) is implemented and run on the testing data to study the behaviour of the route efficiency (E) of all multipath extensions of the third direction of route maintenance except ORMAD in terms of three input parameters M_{eo}, M_{em} and T_e. Different scenarios are involved using a combination of various ranges (high-medium-low) of the parameters. Finally, Equation (6.33) is implemented and run on the testing data to prove the performance of ORMAD against other multipath AODV extensions in terms of route efficiency ratio (E_{ratio}).

7.4.1 Input parameters and performance metrics

Input parameters used in the ORMAD study were as the following:

- Connection ratio η
- Mobility ratio μ
- RDP waiting time ratios T_o
- RMP waiting time ratios T_m
- Route efficiency waiting time ratio T_e

- Multipath degree λ

Supplementary input parameters that are estimated from the analytical formalising are as follows:

- Total number of routes in RDP M_o
- Total number of routes in RMP M_m
- Number of efficient routes of RDP M_{eo}
- Number of efficient routes of RMP M_{em}

Performance metrics used for ORMAD study are as follows:

- Total number of routes M_t during both RDP and RMP.
- Route efficiency E of a multipath routing approach.

7.4.2 Rate of change of MDG

Equation (6.35) is implemented as shown in Figure 7.44 which shows the rate of change of MDG with respect to the mobility ratio ($\frac{\partial\lambda}{\partial\mu}$) using various scenarios of η and T. It increases dramatically with increasing in the mobility ratio. Thus, it is concluded that the rate of change of MDG is affected by mobility ratio more than connectivity and waiting time ratios especially in the low mobility scenarios.

7.4.3 Behaviour of the total number of multiple routes

The behaviour of the total number of multiple routes (M_t) in multipath AODV extensions is tested by implementing (6.12) and running it on the testing data using three input parameters η, μ, T_m and T_o. The other parameters in (6.12) M_o, M_m, C_o and C_m are fixed during the testing process as they are constants.

As shown in Figure 7.45, the maximum value of M_t is 65 which is reached at η = 0.9, T_m= 0.1, T_o= 0.9, and μ= 0.1 (high connectivity ratio, low T_m, high T_o and

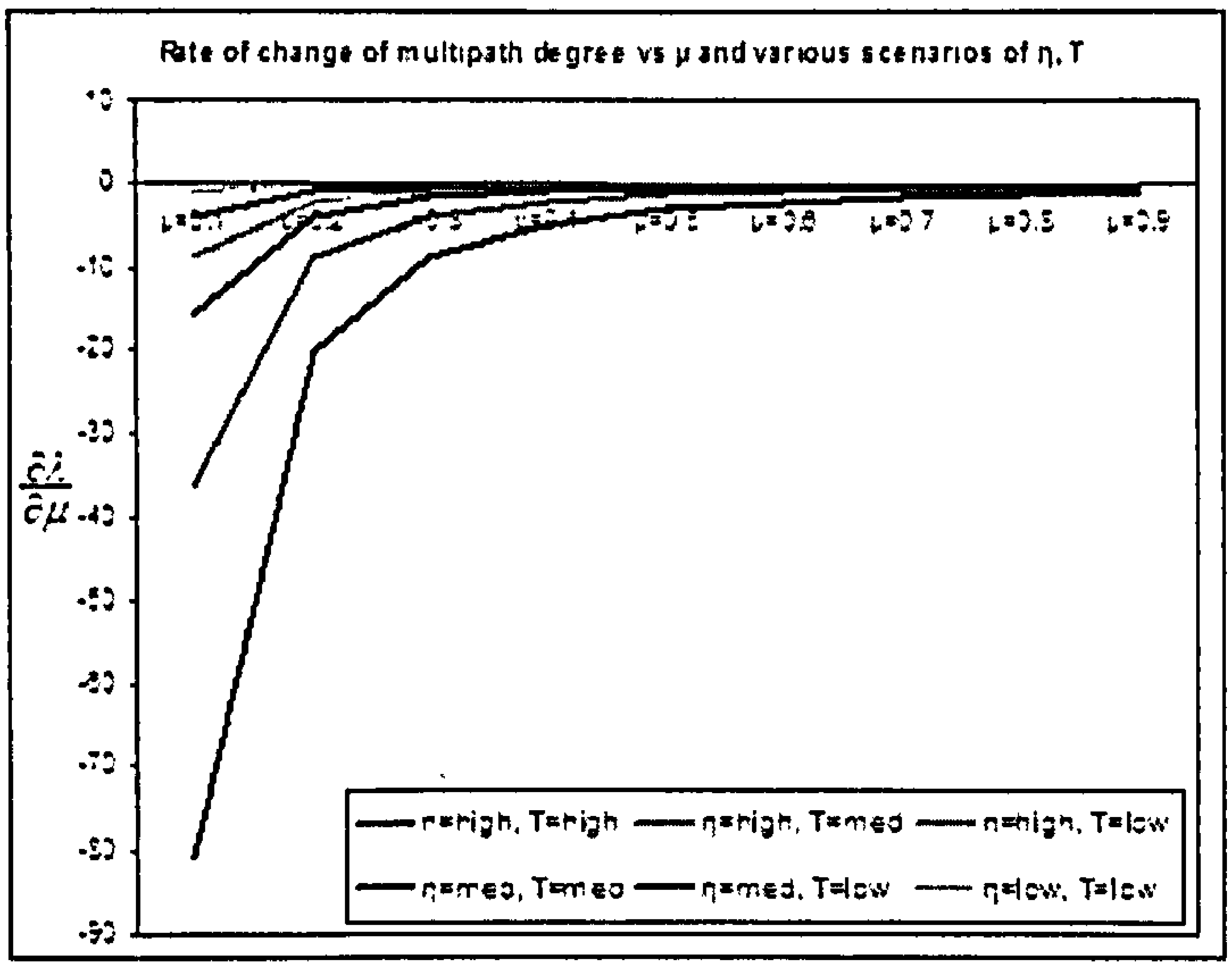

Figure 7.44: Rate of change of λ with respect to μ

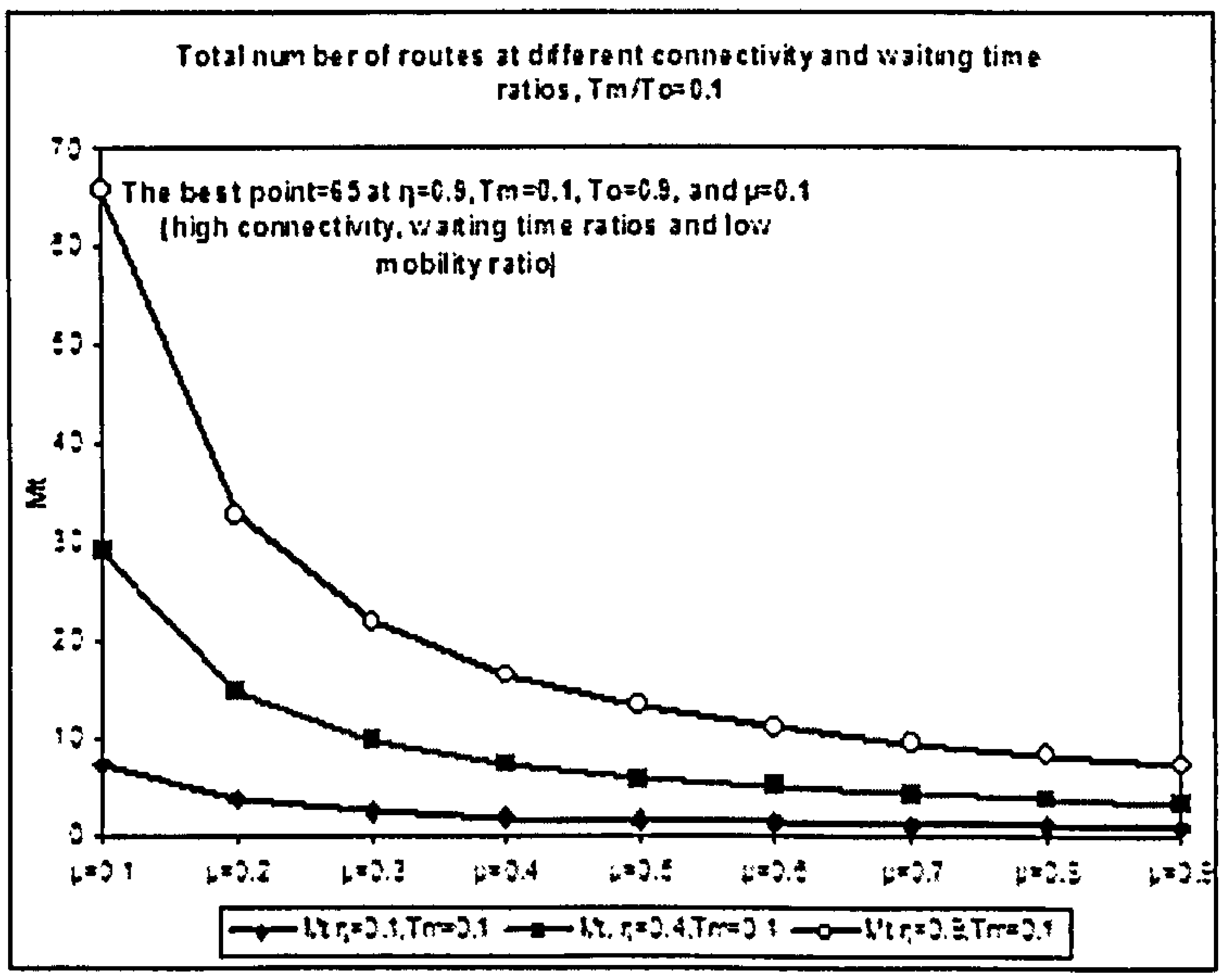

Figure 7.45: M_t at a range of η values and low/high T_m/T_o

low mobility ratio). Figure 7.46 shows that the maximum value of M_t is 90 which is reached at $\eta = 0.9$, $T_m = 0.4$, T_o =0.9 and $\mu = 0.1$ (high connectivity ratio, medium T_m, high T_o and low mobility ratio). Figure 7.47 shows that the maximum value of M_t is 140 which is reached at $\eta = 0.9$, $T_m = 0.9$, $T_o = 0.9$ and $\mu = 0.1$ (high

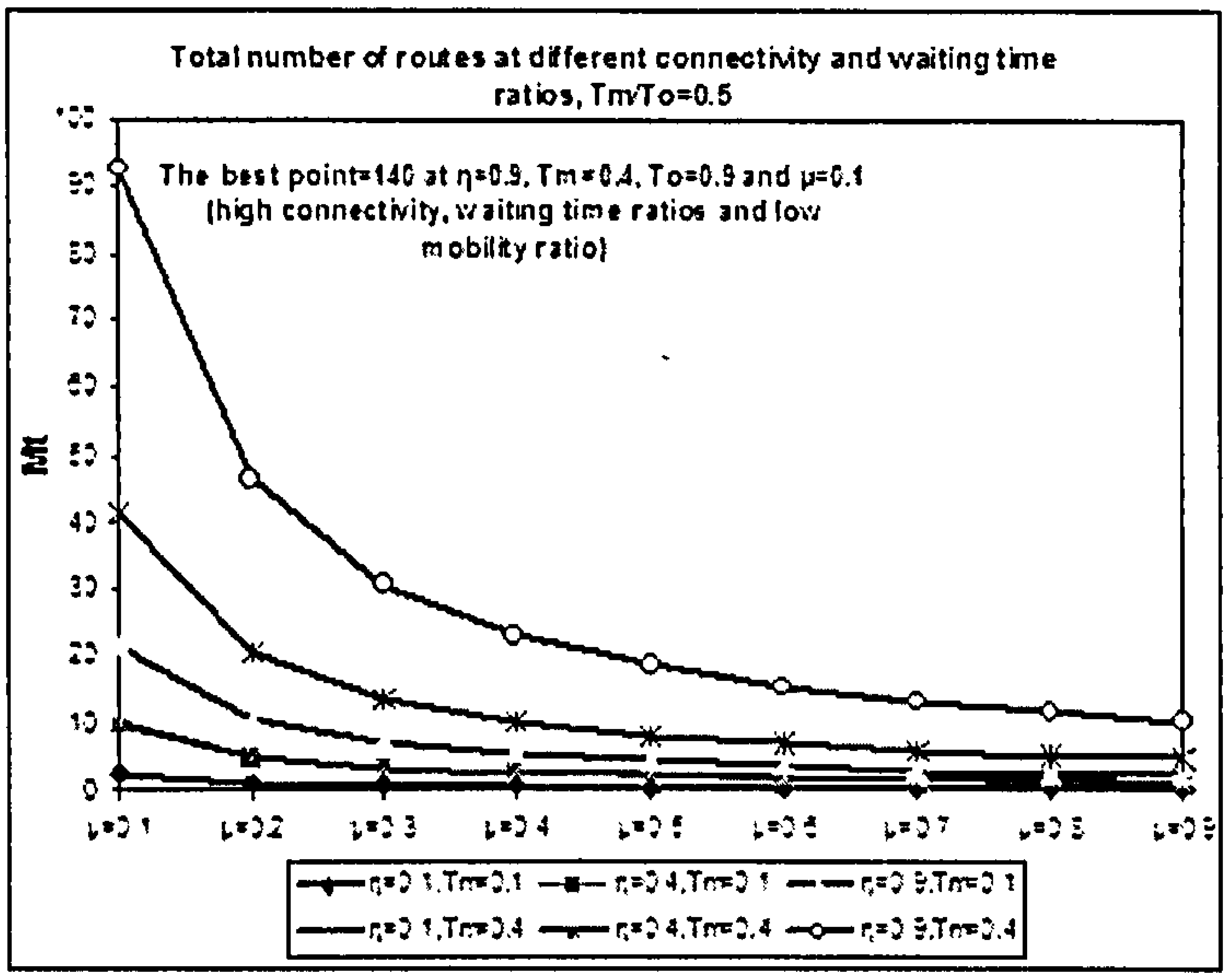

Figure 7.46: M_t at a range of η values and medium/high T_m/T_o

connectivity ratio, high T_m, high T_o and low mobility ratio) and thus, it is clear that the global maximum result of M_t is reached at high connectivity ratio, high waiting time ratios (both of T_m and T_o), and low mobility ratio.

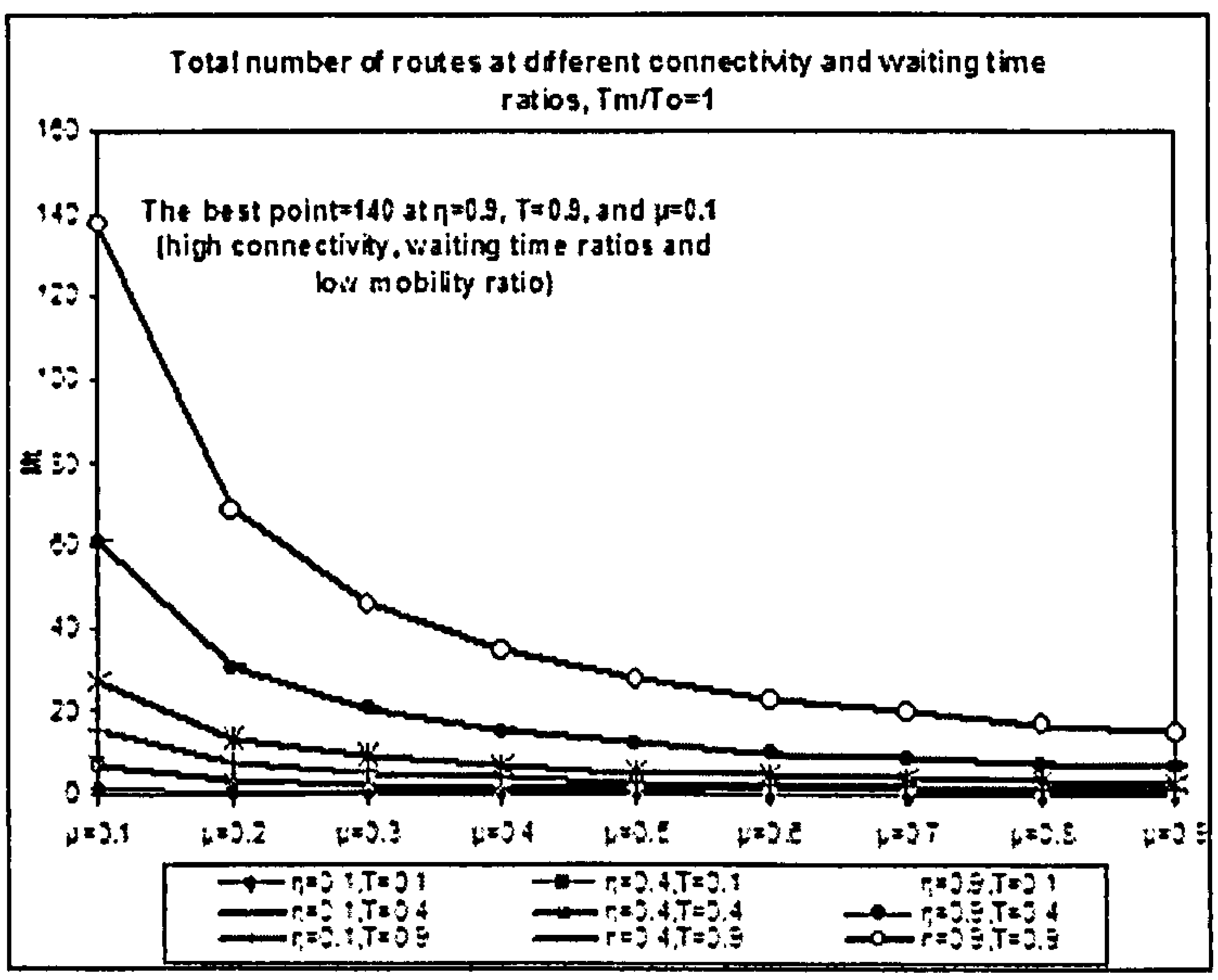

Figure 7.47: M_t at a range of η values and high/high T_m/T_o

7.4.4 Behaviour of the route efficiency

Route efficiency (E) of AODV extensions of the third direction of route maintenance is tested according to (6.27) by varying three input parameters M_{eo}, M_{em} and T_e ($\frac{T_m}{T_o}$) in a wide range of values (low-medium-high). The other parameters in (6.27), M_o, M_m and C_e are fixed during the testing process as they are constants.

Figure 7.48 shows that the maximum value of the route efficiency E at low waiting time ratio T_e is 0.524 under the ideal circumstances (at high M_{em} and M_{eo}). Figure

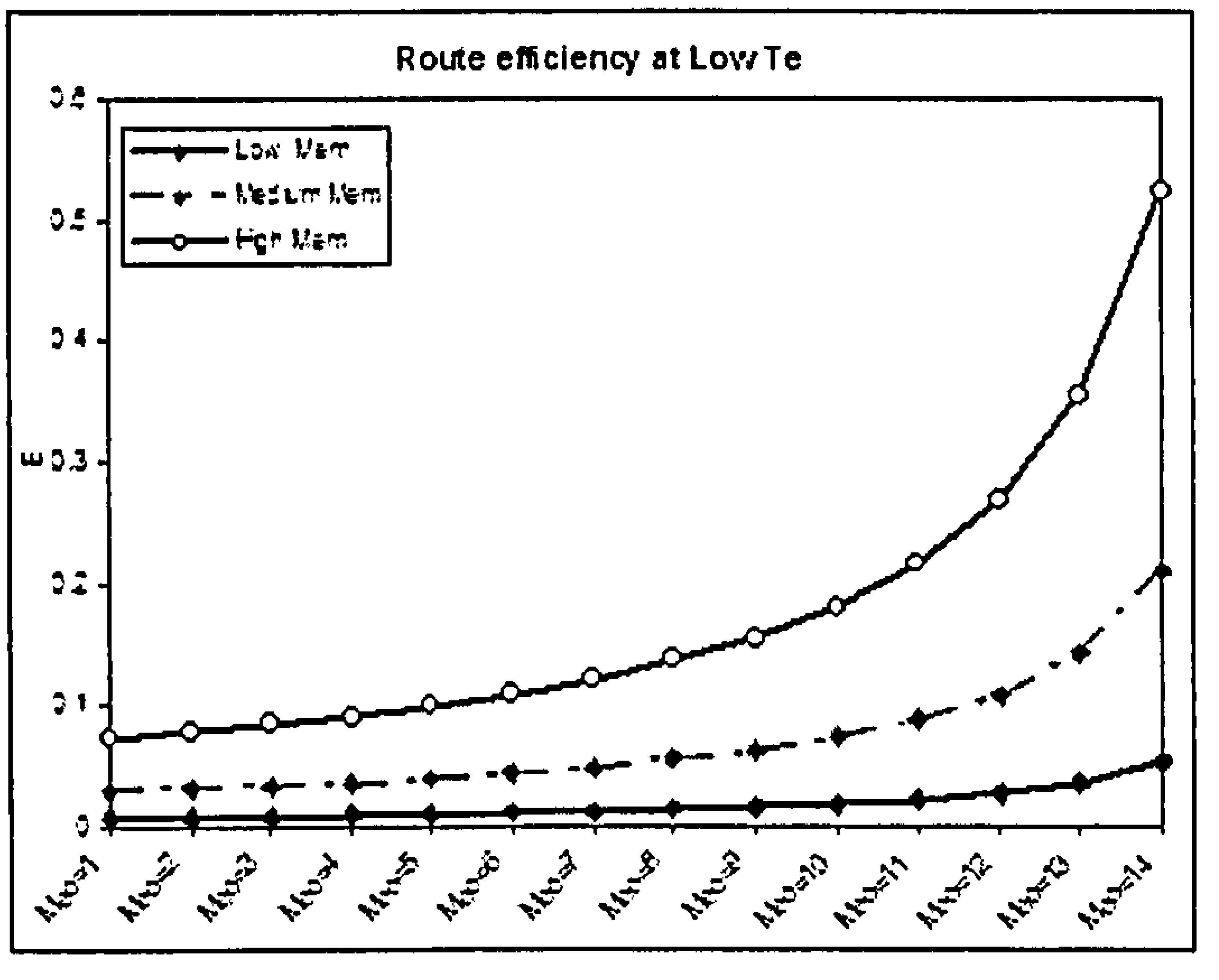

Figure 7.48: E in multipath AODV extensions at low T_e

7.49 shows that the maximum value of the route efficiency E at medium waiting time ratio T_e is 0.815 under the ideal circumstances (at high M_{em} and M_{eo}). Figure 7.50 shows that the maximum value of the route efficiency E at high waiting time ratio T_e is 0.909 under the ideal circumstances (at high M_{em} and M_{eo}).

7.4.5 Route efficiency of ORMAD

Equation (6.32) shows that there is a linear relationship between route efficiency and M_{em} in ORMAD. Route efficiency in (6.32) does not depend on M_{eo} which means that, unlike other extensions, route efficiency in ORMAD is not affected by the initial

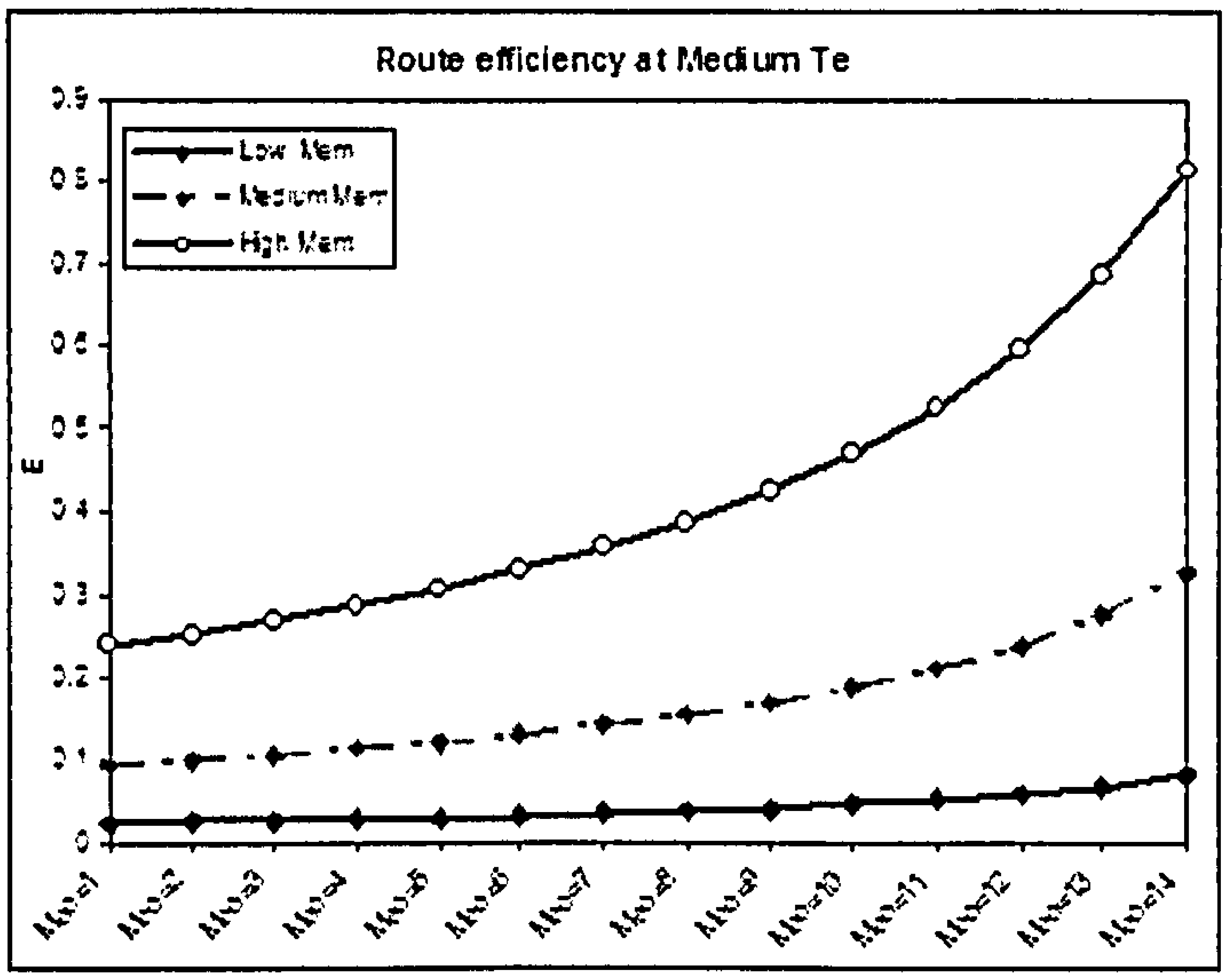

Figure 7.49: E in multipath AODV extensions at medium T_e

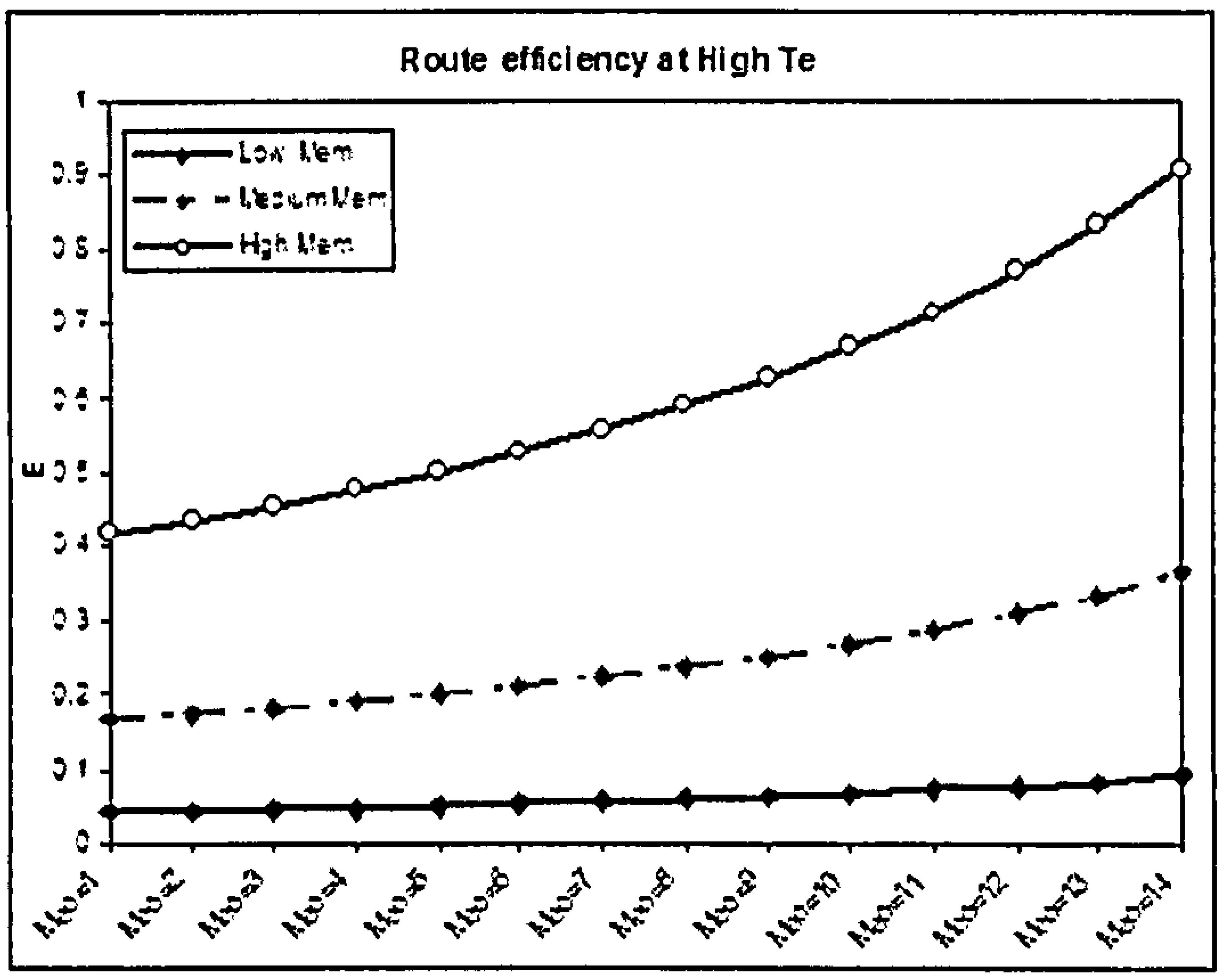

Figure 7.50: E in multipath AODV extensions at high T_e

state of routes. Evaluation of route efficiency ratio of other AODV extensions against ORMAD that are expressed in (6.33) is shown in Figure 7.51.

It is clear that ORMAD mechanism outperforms other AODV extensions with regard to route efficiency which is increased by 1.67 times ($\frac{E_{ORMAD}}{E_{Others}} = 1.67$ or $\frac{E_{Others}}{E_{ORMAD}} = 0.6$) in the worst case (where $T_e = 1$) and by 7.14 times in the best case (where $T_e =$

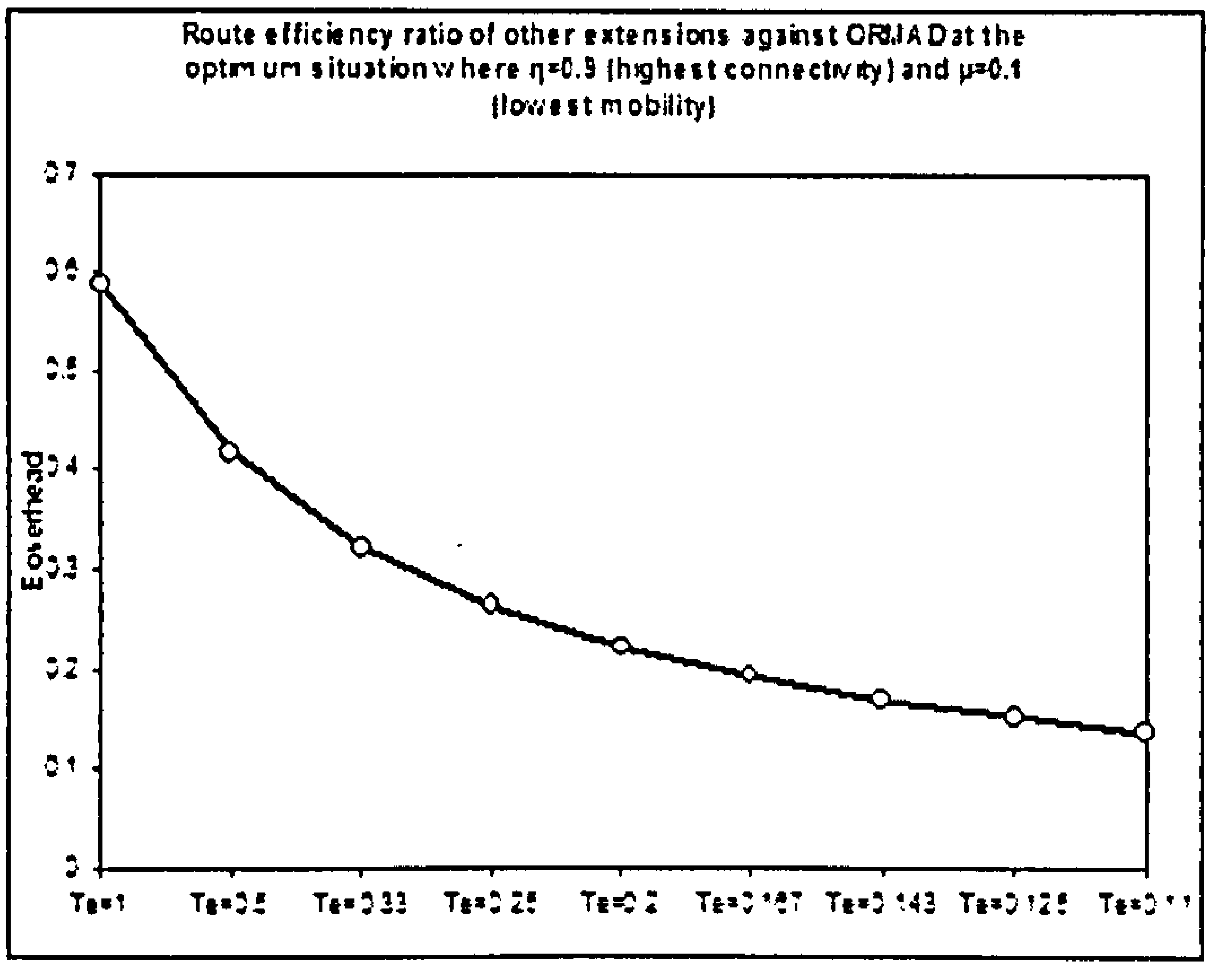

Figure 7.51: E_{ratio} of AODV extensions vs. ORMAD

0.11). It is concluded from Figure 7.51 that the worst case of ORMAD against other extensions can be reached when $T_e = 1$. As shown in Figure 7.50, route efficiency of the other extensions can reach its best case at this ratio. This means that ORMAD outperforms other AODV extensions even in the high waiting time scenarios and thus, ORMAD decreases the waiting time overhead.

Chapter 8

Conclusions and Future Work

8.1 Conclusions

Two novel multipath routing approaches are developed in this thesis as new multipath extensions to AODV routing protocol in MANETs, one of them is developed to optimise route discovery process and the other is developed to optimise route maintenance process in multipath extensions to AODV. The first approach is called TRAODV which is a link-disjoint approach that tries to improve routing overhead in RDP by detecting the waiting time required to receive threshold number of efficient routes. In TRAODV, waiting time is calibrated until receiving a threshold number of efficient routes.

The second approach is called ORMAD which is an extension to TRAODV that optimises routing packets and delay overhead by improving the RMP of TRAODV. ORMAD applies the concepts of threshold waiting time, threshold number of efficient routes, and threshold hop count on the two phases; RDP and RMP. It applies a RMP by invoking a local route repair procedure only to efficient routes which are selected in the RDP and when a route fails, it invokes a local repair procedure between upstream and downstream nodes of the broken link. This mechanism produces a set of alternative subroutes with less number of hops which enhances route efficiency and consequently minimises the routing overhead.

Simulations are carried out for TRAODV using of NS2.26 under Linux platform of Fedora 5 to evaluate the performance of TRAODV against some existing extensions to AODV, namely MRAODV, AOMDV in addition to the traditional multipath protocols DSR, and TORA. Simulation results show that TRAODV reduces the overall routing packets overhead compared to AOMDV and MRAODV, especially for large network size and high mobility. A significant drawback of TRAODV is the reducing in its performance compared to AOMDV and MRAODV in terms of the average end-to-end delay. Another drawback of TRAODV is that it still has less performance in terms of routing packets overhead compared to the traditional multipath protocol TORA . Simulation results of TRAODV show also that the average number of routes stored in a routing table of MRAODV protocol is always larger than the average number of routes in TRAODV. The reason for that is to store and employ all routes in MRAODV including efficient and inefficient routes while the efficient routes only are stored and employed in TRAODV. Performance evaluation of TRAODV and MRAODV shows clearly the effect of the routing mechanism on the performance of each protocol.

ORMAD is implemented and simulated using NS2 and the same environment of TRAODV simulations. The aim of developing ORMAD is to reduce routing packets overhead and average end-to-end delay overhead which are associated with TRAODV as significant drawbacks. The results of ORMAD performance are evaluated against AOMDV, MRAODV, DSR, and TORA protocols. The implementation of TRAODV is modified for ORMAD simulation by extending the RREP waiting time parameter in RMP and applying the local repair procedure only to efficient routes stored in the routing table. Simulation results show that ORMAD enhances the performance of routing packets overhead compared to TRAODV. The performance of ORMAD in terms of routing packets overhead is the closest to TORA performance, however it still less than the performance of the traditional protocol TORA. Moreover, the performance of ORMAD in terms of average end-to-end delay is enhanced ORMAD compared to TRAODV, MRAODV, and AOMDV, especially in high mobility scenarios while the performance of TRAODV and ORMAD converges together in low and medium mobility. Simulation results of ORMAD also show that the performance is affected by varying the two RREP waiting times of both RDP and RMP in different scenarios. As shown by results, short and long waiting times in both phases RDP and RMP tend to less performance in terms of routing packets overhead while the moderate waiting times tend to better performance.

An analytical model is also presented in this thesis for ORMAD approach to describe the whole process of multipath routing in ORMAD, especially the two main core phases of multipath routing; route discovery process and route maintenance process. In addition, the analytical model describes how these two phases interact with each other in terms of two performance metrics; the total number of detected routes and route efficiency.

The analytical model of ORMAD involves the RDP mechanism which is addressed by TRAODV. The total number of routes and route efficiency are analysed in the analytical model for connectivity, mobility, and waiting time ratios. The analytical model is implemented and tested using Matlab and the results are evaluated for ORMAD against other multipath extensions AODV. It is concluded from the results study that the total number of routes is affected by the mobility more than connectivity and waiting time ratios. Route efficiency in multipath AODV extensions is affected only by the ratio of the waiting time of local route discovery process with respect to the waiting time of general route discovery process and number off efficient routes detected in a route maintenance process. ORMAD mechanism outperforms the mechanism of other multipath extensions to AODV in terms of maximising route efficiency, especially in low waiting time ratio of route maintenance process, which may lead to minimise the overhead of repairing inefficient routes.

8.2 Future Work

Multipath routing in MANETs is promising for so many applications in different areas of wireless networks thus, there are many trends of multipath routing in MANETs, especially in routing disjointness for reliability, improving QoS, increasing power conservation, help in security strengthen, increasing reliability in hybrid networks and finally, in many applications and design issues of wireless mesh and sensor networks.

As a future work of this research, a simulation-based study can be carried out to estimate the percentage of effective routes that might be lost by reducing waiting time in TRAODV. A fuzzy logic approach may be useful for a TRAODV extension that can be developed to improve its RDP by detect the optimal waiting time needed to receive the optimum threshold number of efficient routes which are almost needed by a source node. The selection criteria of multiple routes may be improved in TRAODV by involving the mobility and the energy of the nodes as new parameters which may optimise the estimation of threshold hop count.

ORMAD can be extended using a fuzzy logic approach to optimise the waiting time needed by the route maintenance process so that some sort of balance may be achieved between the time of local repairing and the life time of efficient routes. A fuzzy logic approach can be also developed to determine the optimal ratio of the two waiting times in both RDP and RMP which can achieve a significant enhancement in both routing packet overhead and average end-to-end dely overhead in ORMAD approach.

Finally, a simulation study can be applied to TRAODV and ORMAD individually involving traffic allocation component of routing, node-disjoint, and node-disjoint in the simulation study for some applications of MANETs such as heavy traffic multimedia and real-time transmission. An evaluation can be performed for TRAODV and ORMAD approaches against some existing protocols to evaluate the feasibility of utilising efficient routes in such applications.

Bibliography

[1] P. Mohapatra, S. V. Krishnamurthy, "Ad Hoc Networks Technologies and Protocols", Springer, 2005.

[2] C. S. R. Murthy and B. Manoj, "Ad Hoc Wireless Networks: Architectures and Protocols", Prentice Hall PTR, May 2004.

[3] C. E. Perkins, "Ad Hoc Networking", Addison Wesley Professional, December 2000.

[4] IETF Working Group: Mobile Adhoc Networks (manet). *http : //www.ietf.org/html.charters/manet – charter.html.*

[5] P. Nicopolitidis, M. S. Obaidat, G. I. Papadimitriou and A. S. Pomportsis, "Wireless Networks", John Wiley and Sons, Ltd, 2003.

[6] S. K. Sarkar, T. G. Basavaraju, C. Puttamadappa, "Ad Hoc Mobile Wireless Networks: Principles, Protocols, and Applications", Auerbach Publications Taylor & Francis Group, 2008.

[7] S. Basagni, M. Conti, S. Giordano, I. Stojmenovic, "Mobile Ad Hoc Networking", A John Wiley and Sons, Inc., Publication, 2004.

[8] Mohammad Ilyas, "The Handbook of Ad Hoc Wireless Networks", CRC Press, 2003.

[9] Georgios Parissidis, Vincent Lenders, Martin May and et al., "Multi-path Routing Protocols in Wireless Mobile Ad Hoc Networks: A Quantitative Comparison", NEW2AN 2006, LNCS 4003, pp. 313326, Springer-Verlag Berlin Heidelberg, 2006.

[10] S. Kami Makki, Peter Reiher, Kia Makki et al., "Mobile and Wireless Network Security and Privacy", Springer Science and Business Media, LLC, 2007.

[11] Stephen Mueller, Rose P. Tsang, and Dipak Ghosal, "Multipath Routing in Mobile Ad Hoc Networks: Issues and Challenges", White paper funded by University of California, Davis and Sandia National Laboratories, Livermore Sandia National Laboratories, CA, USA, 2004. URL: *www.cs.ucdavis.edu/ ghosal/Research/publications/stephen–lncs–multipath–survey – paper –* 2004*.pdf*

[12] Charles E. Perkins, Elizabeth M. Royer, Samir R. Das, "Ad Hoc On-demand Distance Vector Routing", October 99 IETF Draft, 33 pages. The latest draft is Internet RFC 3561, July 2003. On the URL: *http : //www.ietf.org/internet – drafts/draft – ietf – manet – aodv –* 14*.txt.*

[13] H. Higaki and S. Umeshima, "Multiple-Route Ad hoc On-Demand Distance Vector (MRAODV) Routing Protocol", Proceedings of the 18th International Parallel and Distributed Processing Symposium (IPDPS04), IEEE, 2004.

[14] Shih-Lin Wu , Yu-Chee Tseng, "Wireless Ad Hoc Networking", Auerbach Publications -Taylor and Francis Group, 2007.

[15] D.B. Johnson and D.A. Maltz, "Dynamic Source Routing in Ad Hoc Wireless Networks", Mobile Computing, vol. 353. Kluwer Academic, 1996.

[16] V. D. Park and M. S. Carson, "A highly Adaptive Distributed Routing Algorithm for Mobile Wireless Networks", Proc. INFOCOM 97, Apr. 1997.

[17] Mahesh K. Marina, and Samir R. Das, "On-demand Multipath Distance Vector Routing in Ad Hoc Networks", Proceedings of the 9th IEEE International Conference on Network Protocols (ICNP), November 2001.

[18] Ming Liu, Zhiyan Xu, Junli Yang and et al., "Collision-constrained Minimum Energy Node-disjoint Multipath Routing in Ad Hoc Networks", Proceedings of IEEE, 2006.

[19] European Telecommunications Standardisation Institute (ETSI), "High Performance Radio Local Area Network Type 2 (Hiperlan2)", Broadband Radio Access Networks (BRAN) project, 1999.On the URL:*http : //portal.etsi.org/archived/radio/hiperlan/hiperlan.asp*

[20] *www.ieee*802.*org*/11.

[21] Dmitri D. Perkins, Herman D. Hughes and Charles B. Owen, "Factors Affecting the Performance of Ad Hoc Networks", IEEE internet computing, East Lansing, 2002, MI 48824-1226.

[22] R. Negi and A. Rajeswaran, "Capacity of power constrained ad-hoc networks", Proceedings of IEEE Infocom, 2004.

[23] J. Jubin and J.D. Tornow, "The DARPA Packet Radio project", Proceedings of the IEEE, 1987.

[24] IEEE 802.11 Working Group, *http : //www.manta.ieee.org/groups/*802/11/.

[25] Magnus Frodigh, Per Johansson and Peter Larsson, "Wireless ad hoc networkingThe art of networking without a network", Ericsson Review No. 4, 2000.

[26] Norihiko Morinaga, Ryuji Kohno, Seiichi Sampei, "Wireless Communication Technologies : New Multimedia Systems", Kluwer Academic Publishers, 2002.

[27] IETF, "RFC 2501 - Mobile Ad hoc Networking (MANET): Routing Protocol Performance Issues and Evaluation Considerations", January 1999, *http : //www.ietf.org/rfc/rfc2501.txt.*

[28] Ramin Hekmat, "Ad-hoc Networks: Fundamental Properties and Network Topologies", A book published by Springer, 2006.

[29] M. S. Corson, S. Batsell, and J. Macker, "Architectural Considerations for Mobile Mesh Networking", in Proceedings IEEE MILCOM 96.

[30] Cathy Spearmon, "Understanding Hybrid Wireless-Wired Networks", An article published in BellaOnline's Computer Networks Site, 2007. URL: *http : //www.bellaonline.com/articles/art43047.asp.*

[31] Zygmunt J. Haas, "Ad Hoc Networks - A New Communication Paradigm", A Presentation of Wireless Networks Laboratory, School of Electrical Engineering, Cornell University, no date, It can be downloaded from the Website *www.ee.cornell.edu/ haas/wnl.html.*

[32] Nitin H. Vaidya, "Mobile Ad Hoc Networks", A Seminar Presentation of MANET Tutorial in Texas A & M University, 2000, It can be downloaded from the Website *http : //www.cs.tamu.edu/faculty/vaidya.*

[33] Satyabrata Chakrabarti and Amitabh Mishra, "QoS Issues in Ad Hoc Wireless Networks", IEEE Communications Magazine, February 2001.

[34] Lidong Zhou, Zygmunt J. Haas, "Securing Ad Hoc Networks", IEEE network, special issue on network security, November/December, 1999.

[35] Levente Buttyan and Jean-Pierre Hubaux, "Security and Cooperation in Wireless Networks, Thwarting Malicious and Selfish Behavior in the Age of Ubiquitous Computing", A Graduate Textbook, Available on *http : //secowinet.epfl.ch* under a permission from Cambridge University Press, Draft Version 1.3, Feb. 2007.

[36] Kaarle Ritvanen, "Multicast Routing and Addressing", Helsinki University of Technology Department of Computer Science and Engineering, A Seminar on Internetworking, 26-27/4/2004.

[37] Curt White, "Data Communications and Computer Networks", Published by Thomson, Third Edition, 2002.

[38] A. Tanenbaum, "Computer Networks", Englewood Cliffs, NJ: Prentice Hall, 1988.

[39] David A. Maltz, "On-Demand Routing in Multi-hop Wireless Mobile Ad Hoc Networks", A Ph.D. thesis, School of Computer Science, Carnegie Mellon University, May, 2001.

[40] Ankur Khetrapal, Routing techniques for Mobile Ad Hoc Networks Classification and Qualitative/Quantitative Analysis, Delhi College of Engineering, Delhi University, 2003.

[41] Dipesh Patel ,Dr. Rakesh Nagi, "Ad hoc Wireless Networks", University at Buffalo (SUNY), Department of Industrial Engineering, October 17, 2001. Available on *http : //www.acsu.buffalo.edu/ nagi/courses/684/adhoc.pdf.*

[42] Mohammed Husein Alchaita, "Routing and Mobility Strategies for Mobile Ad Hoc Networks", PhD thesis, De Montfort University, Sep. 2006.

[43] Mesut Gne, "Routing Algorithms for Mobile Multi-Hop Ad-Hoc Networks", IEEE Trans. on Internet Computing, Vol. 3, No. 4, July/August 1999, pp.

[44] *www.nist.gov/*, Web site owner: The National Institute of Standards and Technology.

[45] Victor 0. K. Li, Z. Lu Ad Hoc Network Routing, International Conference on Networking, Sensing and Control, IEEE, 2004.

[46] *www.cisco.com*, Cisco Systems, Inc.

[47] Sumesh J. Philip, "Routing in Mobile Ad hoc Networks", Lecture notes, CSE620 Fall 2004, State University of New York ,University at Buffalo, 2004. URL: *www.cse.buffalo.edu/ qiao/cse620/fall04/ad_hoc.ppt.*

[48] Elizabeth M. Royer, Chai-Keong Toh, A Review of Current Routing Protocols for Ad Hoc Mobile Wireless Networks ,Georgia Institute of Technology IEEE Personal Communications, April 1999.

[49] C.E. Perkins, T.J. Watson, "Highly dynamic destination sequenced distance vector routing (DSDV) for mobile computers", ACM SIGCOMM94 Conference on Communications Architectures, London, UK, 1994.

[50] S. Murthy J.J. Garcia-Luna-Aceves, "A routing protocol for packet radio networks", in: Proceedings of the First Annual ACM International Conference on Mobile Computing and Networking, Berkeley, CA, 1995, pp. 8695.

[51] Z. J. Haas and M. R. Pearlman, "Zone Routing Protocol for Ad Hoc Networks", tech. rep., Internet Engineering Taskforce (IETF), Nov. 1997.

[52] Y.-B. Ko, N.H. Vaidya, "Location-aided routing (LAR) in mobile ad hoc networks", in: Proceedings of the Fourth Annual ACM/IEEE International Conference on Mobile Computing and Networking (Mobicom'98), Dallas, TX,1998.

[53] M. Abolhasan, T. Wysocki and E. Dutkiewicz, "A review of routing protocols for mobile ad hoc networks", Ad Hoc Networks 2 (2004) 122 , Elsevier, 2004.

[54] C. C. Chiang, "Routing in clustered multihop mobile wireless networks with fading channel", in: Proceedings of IEEE SICON, April 1997, pp. 197211.

[55] Yashar Ganjali and Abtin Keshavarzian, "Load Balancing in Ad Hoc Networks: Single-path Routing vs. Multi-path Routing", IEEE INFOCOM, 2004.

[56] Mehdi Alilou and Mehdi Dehghan.t, "Upgrading Performance of DSR Routing Protocol in Mobile Ad Hoc Networks", Proceedings of World Academy of Science - Engineering adn Technology Volume 5 April 2005 - ISSN 1307-6884.

[57] R.E. Bellman, "Dynamic Programming", Princeton University Press, Princeton, NJ, 1957.

[58] L.R. Ford, D.R. Fulkerson, "Flows in Networks", Princeton University Press, Princeton, NJ, 1962.

[59] Santhosh R. Thampuran, "Routing Protocol for Ad hoc Network of Mobile Nodes", Department of Electrical and Computer Engineering University of Massachusetts, 1999.

[60] Soumendra Nanda, "Spatial Multipath Location Aided Routing", Master Thesis, Dartmouth College, Hanover, New Hampshire, USA, June 3rd 2004.

[61] Azzedine Boukerche, "Handbook of Algorithms for Wireless Networking and Mobile Computing", CHAPMAN and HALL/CRC Taylor and Francis Group, 2006.

[62] Ruay-Shiung Chang and Shing-Jiuan Leu, "Long-lived Path Routing With Received Signal Strength for Ad Hoc Networks", IEEE Proceedings, 2006.

[63] Padmini Misra, "RoutFing Protocols for Ad Hoc Mobile Wireless Networks", A Paper available on: *http : //www.cis.ohio − state.edu/ jain/cis*788 − 99*/adhoc_routing/index.html*, 2/7/2000.

[64] Tony Larsson, Nicklas Hedman, "Routing Protocols in Wireless Ad-hoc Networks - A Simulation Study", Lulea University of technology, master thesis, 1998.

[65] I. Chakeres and C. Perkins, "Dynamic manet on-demand (dymo) routing", 2006. *http : //www.ietf.org/internet − drafts/draft − ietf − manet − dymo −* 13*.txt*.

[66] Azzedine Boukerche, "A Performance Comparison of Routing Protocols for Ad Hoc Networks", Parallel Simulations and Distributed Systems (PARADISE), Research Laboratory, University of North of Texas, IEEE, 2001.

[67] Samba Sesay, Zongkai Yang, Biao Qi and Jianhua He, Simulation Comparison of Four Wireless Ad hoc Routing Protocols, Information Technology Journal 3 (3): 219-226, 2004.

[68] Rajiv Misra and C. R. Mandal, Performance comparison of AODV/DSR on-demand Routing protocols for ad hoc networks in constrained situation, ICPWC05, 2005.

[69] Li Layuan, Li Chunlin, Yaun Peiyan, Performance evaluation and simulations of routing protocols in ad hoc networks, Elsevier, Computer Communications 30 (2007) 18901898.

[70] Esmaeili, M., Abbaspour, M., Alipour, H. et al., "Challenge in QoS Supporting via Integrating Differentiated Service and Multipath Routing on Mobile Ad Hoc Network", Seventh International Conference on Computer and Information Technology, IEEE, 2007.

[71] Network Simulator ns-2, $http://www.isi.edu/nsnam/ns/$.

[72] NS2 Folder: $ns/indep-utils/cmu-scen-gen/cbrgen.tcl$.

[73] NS2 Folder: $ns/indep-utils/cmu-scen-gen/setdest/setdest.exe$.

[74] Timo Viipuri, "A Case Study of Simulating DiffServ in NS-2", Netlab, TKK, Finland, 26-11-2002, Published on the URL: $http://www.netlab.tkk.fi/opetus/s383180/2005/harj/H3/diffnet.pdf$.

[75] A .L. Cavilla, "MANET extensions to ns2", Department of Computer Science, University of Toronto, 2004, Published on the URL: $www.cs.toronto.edu/\ andreslc/publications/MANET_extensions.pdf$.

[76] T. Camp, J. Boleng, and V. Davies, "A Survey of Mobility Models for Ad Hoc Network Research", Wireless Communications and Mobile Computing (WCMC): Special issue on Mobile Ad Hoc Networking: Research, Trends and Applications, vol. 2, no. 5, 2002, pp. 483-502.

[77] Fang Jing, R.S. Bhuvaneswaran, Yoshiaki Katayama et al., "Multipath Routing Selection Strategies in Wireless Mobile Ad Hoc Networks", IEEE ICSCN 2007, MIT Campus, Anna University, Chennai, India, Feb. 22-24, 2007. pp. 117-121.

[78] Madhavi W. Subbarao, "Ad Hoc Networking Critical Features and Performance Metrics", Wireless Communications Technology Group, NIST, October 7, 1999.

[79] $http://hpds.ee.ncku.edu.tw/\ smallko/ns2/adhoc_routing.htm$

[80] G. H. Ash, A. H. Kafker and K. R. Krishnan, "Servicing and Real-Time Control of Networks with Dynamic Routing", Bell System Technical Journal, Vol. 60, No. 8, 1981.

[81] R. J. Gibbons, F. P. Kelley, P. B. Key, "Dynamic Alternative Routing - Modelling and Behavior", Proceedings of the 12th International Teletraffic Conference, 1988.

[82] R.C. Ogier and V. Ruthenburg, "Minimum-expected-delay alternate routing", In IEEE INFOCOM92, Florence, Italy, IEEE,1992.

[83] R. Rom, I. Cidon and Y. Shavitt, "Analysis of multi-path routing", IEEE/ACM Transactions on Networking, 7(6):885896, 1999.

[84] ATM Forum, "ATM user-network interface specification", Version 3.0, 1993.

[85] T. Clausen, P. Jaqcuet, A. Laouiti, P. Minet, P. Muhlethaler, A. Qayyum, and L. Viennot, "Optimized link state routing protocol (OLSR)", RFC 3626, Oct. 2003.

[86] H. M. P. Shekhar and K S. Ramanatha, "Mobile Agents Aided Congestion Aware Multipath Routing in Mobile Ad Hoc Networks", 9th International Conference on Telecommunications - ConTEL 2007, June 2007.

[87] S. Lin, Y. Wang, S. Panwar and et al., "video transport over ad-hoc networks using multiple paths", Invited paper in the Proceedings of the 2002 IEEE International Symposium on Circuits and Systems, Scottsdale, Arizona, May 2002, pp.57-60.

[88] Sasan Adibi and Shervin Erfani, "A Multipath Routing Survey for Mobile Ad-Hoc Networks", 1-4244-0086-4/05, IEEE Proceedings, 2005.

[89] Ye, Z., Krishnamurthy, S. V., Tripathi, S.K., "A Framework for Reliable Routing in Mobile Ad Hoc Networks", IEEE INFOCOM, 2003.

[90] A. Tsirigos And Z. J. Haas, "Multipath Routing in the Presence of Frequent Topological Changes", IEEE Communications Magazine, Nov. 2001, pp. 132-138.

[91] A. Nasipuri and S. R. Das, "On-demand multipath routing for mobile ad hoc networks", Proc. IEEE ICCCN, 1999, pp. 6470.

[92] Xuefei Li and Laurie Cuthbert, "Stable Node-Disjoint Multipath Routing with Low Overhead in Mobile Ad hoc Networks", Proceedings of the The IEEE Computer Societys (MASCOTS04), 2004.

[93] Leung, R., Liu, J., Poon, E., Chan, A.-L.C., Li, B., "MP-DSR: A QoS-aware Multipath Dynamic Source Routing Protocol for Wireless Ad-hoc Networks", Proceedings of the 26th IEEE Annual Conference on Local Computer Networks (2001) 132-141.

[94] Canfeng Chen, Jian Ma, Weiling Wu and et al., "A Modeling Framework for Multipath Routing in Ad Hoc Networks", IEEE GLOBECOM proceedings, 2005.

[95] Peter P. Pham, Sylvie Perreau, "Increasing the network performance using multipath routing mechanism with load balance", Elsevier Journal of Ad Hoc Networks 2 (2004) 433459.

[96] Salma Ktari, Houda Labiod and Mounir Frikha, "Load Balanced Multipath Routing in Mobile Ad hoc Network", in IEEE Proceedings, 2006.

[97] Yang-Min Lee, Bong-Soon Kang, Jae-Kee Lee, "Load Balancing Protocol considering effective Path Search in Mobile Ad hoc network", IEEE Proceeding ICACT'07, 2007.

[98] T. W. Chen and M. Gerla, "Global state routing: a new routing scheme for ad hoc wireless networks", Proceedings of IEEE ICC98, August 1998.

[99] M. Gerla, "Fisheye State Routing protocol (FSR) for ad hoc networks", Internet Draft, draft-ietf-manet-aodv-03.txt, 2002.

[100] Frederick Ducatelle, Gianni Di Caro and Luca Maria Gambardella, "Ant Agents for Hybrid Multipath Routing in Mobile Ad Hoc Networks", Wireless Ondemand Network Systems and Services, 2005. WONS 2005. Second Annual Conference on 19-21 Jan. 2005.

[101] G. Pei, M. Gerla, X. Hong, C. Chiang, "A wireless hierarchical routing protocol with group mobility", In: Proceedings of Wireless Communications and Networking, New Orleans, 1999.

[102] M. Joa-Ng and I-Tai Lu, "A peer-to-peer zone-based twolevel link state routing for mobile ad hoc networks", IEEE Journal on Selected Areas in Communications, 17(8):14151425, August 1999.

[103] A. M. Abbas and B. N. Jain, "Analysis of Disjoint Multipath Routing for Mobile Ad hoc Networks", ICPWC05, IEEE, 2005.

[104] Xuefei Li and Laurie Cuthbert, "Node-Disjoint Multipath Routing and Distributed Cross-Layer QoS Guarantees in Mobile Ad hoc Networks", Proceedings of the Seventh ACIS International Conference on Software Engineering, Artificial Intelligence, Networking, and Parallel/Distributed Computing (SNPD06), IEEE, 2006.

[105] Lee, S.J. and Gerlà, M., "AODV-BR: Backup Routing in Ad hoc Networks", Proc. of IEEE Wireless Communications and Networking Conference, pp. 13111316, 2000.

[106] S. Corson and J. Macker, "Mobile ad hoc networking (MANET): Routing protocol performance issues and evaluation considerations", IETF RFC 2501, January 1999.

[107] Ying-Hong Wang, Hung-Zu Lin and Shu-Min, "Interfering-aware QoS Multipath Routing for Ad Hoc Wireless Network", Proceedings of the 18th International Conference on Advanced Information Networking and Application (AINA04), IEEE, 2004.

[108] Wei Wei and Avideh Zakhor, "Multipath Unicast and Multicast Video Communication over Wireless Ad Hoc Networks", Proceedings of the First International Conference on Broadband Networks (BROADNETS04), IEEE, 2004.

[109] Victor C. Frias, Guillermo D. Delgado, and Monica A. Igartua, "Multipath Routing for video-streaming services over IEEE 802.11e Ad hoc Networks", Proceedings of IEEE, 2005.

[110] V. Carrascal Frias, G. Dfaz Delgado, M. Aguilar Igartua, "Multipath Routing with Layered Coded Video to Provide QoS for Video-Streaming over MANETs", Proceedings of IEEE, 2006.

[111] Yifeng He, Ivan Lee, and Ling Guan, "Optimized multi-path routing using dual decomposition for wireless video streaming", Proceedings of IEEE, 2007.

[112] P. Papadimitratos, Z. J. Haas, and E. G. Sirer, "Path set selection in mobile ad hoc networks", in Proc. ACM MobiHOC 2002, Lausanne, Switzerland, June 911, 2002, pp. 160170.

[113] Anand P. Subramanian, Anto A. J., Janani Vasudevan and et al., Multipath Power Sensitive Routing Protocol for Mobile Ad hoc Networks, WONS2004, Madonna di Campiglio, Italy, January 2004.

[114] YUAN Ping, BAI Yu and WANG Haoand, "A Multipath Energy-Efficient Routing Protocol for Ad hoc Networks", Proceedings of IEEE, 2006.

[115] Zhengyu Wu, Xiangjun Dong, Hantao Song and et al., "Ant-based Energy Aware Disjoint Multipath Routing Algorithm in MANETs", 2006 1st International Symposium on Pervasive Computing and Applications, IEEE, 2006.

[116] Wen-Hwa Liao, Yu-Chee Tseng and Jang-Ping Sheu, "GRID:A Fully Location-Aware Routing Protocol for Mobile Ad Hoc Networks", In Telecommunication Systems, 2001.

[117] Seung Jun Baek and Gustavo de Veciana, "Spatial Energy Balancing Through Proactive Multipath Routing in Wireless Multihop Networks", IEEE/ACM Transactions on networking, Vol. 15, No. 1, February 2007.

[118] Li-Ping Chou, Chin-Chi Hsu and Fan Wu, "A Reliable Multi-Path Routing Protocol for Ad-Hoc Networks", Proceedings of IEEE, 2002.

[119] Souheila Buoam and Jalel Ben-Othman, "Data Security in Ad hoc Networks Using MultiPath Routing", Personal, Indoor and Mobile Radio Communications, 2003. PIMRC 2003. 14th IEEE Proceedings on Volume 2, 7-10 Sept. 2003.

[120] Zhi Li and Yu-Kwong Kwok, "A New Multipath Routing Approach to Enhancing TCP Security in Ad Hoc Wireless Networks, Parallel Processing, ICPP 2005 Workshops. International Conference Workshops on 14-17 June 2005.

[121] Li Zhao and Jos G. Delgado-Frias, "Multipath Routing Based Secure Data Transmission in Ad Hoc Networks", Proceedings of IEEE, 2006.

[122] Sebastien Berton, Hao Yin, Chuang Lin and et al., "Secure, Disjoint, Multipath Source Routing Protocol (SDMSR) for Mobile Ad-Hoc Networks", Proceedings of the Fifth International Conference on Grid and Cooperative Computing (GCC'06), IEEE, 2006.

[123] Alex Ali Hamidian, "A Study of Internet Connectivity for Mobile Ad Hoc Networks in NS 2", Master thesis, Dept. of CS, Lund University, Jan 2003.

[124] Jiang, M.H. and Jan, R.H., "An Efficient Multiple Paths Routing Protocol for Ad-hoc Networks", Proc. of the 15th International Conference on Information Networking, pp. 544549, 2001.

[125] H. L. Chen and C. H. Lee, "Two Hops Backup Routing Protocol in Mobile Ad Hoc Networks", The 2005 11th International Conference on Parallel and Distributed Systems (ICPADS05), 2005.

[126] Cheng-Ting Kuo, Chiu-Kuo Liang, "A Multipath Routing Protocol in Mobile Networks", International Conference on Information Technology: Research and Education, IEEE, 2006.

[127] S. J. Lee and M. Gerla, "Split Multipath Routing with Maximally Disjoint Paths in Ad hoc Networks", IEEE ICC 2001, June.2001.

[128] L. Wang, L. Zhang, Y. Shu, and M. Dong, "Multipath source routing in wireless ad hoc networks", Proc. Canadian Conf. Electrical and Computer Engineering, vol. 1, 2000, pp. 479483.

[129] J. Raju and J. J. Garcia-Luna-Aceves, "A new approach to on-demand loop-free multipath routing", in Proc. IEEE ICCCN, Oct. 1999, pp. 522527.

[130] Wang Y. H., Chung C. C., Chuang C. C., "On-demand Ad Hoc Routing Protocol with Backup Node", Proceedings of IEEE TENCON02, 2002.

[131] A. Nasipuri, R. Castaneda, and S.R. Das, "Performance of Multi-path Routing for On-Demand Protocols in Mobile Ad-Hoc Networks", Mobile Networks and Applications, 6:339-349, 2001.

[132] Jie Lia, Yi Panb, Yang Xiaoc, "Performance study of multiple route dynamic source routing protocols for mobile ad hoc networks", Elsevier, J. Parallel Distrib. Comput. 65 (2005) 169 177.

[133] A. Tsirigos And Z. J. Haas ,"Analysis Of Multipath Routing, Part I: The Effect on the Packet Delivery Ratio", IEEE Transactions on Wireless Communications, Vol. 3, No. 1, January 2004.

[134] A. Tsirigos And Z. J. Haas ,"Analysis of Multipath Routing, Part 2: Mitigation of the Effects of Frequently Changing Network Topologies", IEEE Transactions on Wireless Communications, Vol. 3, No. 2, March 2004.

[135] Mika Minematsu, Masato Saito, "Efficient Route Discovery Scheme in Ad Hoc Networks Using Routing History", IEICE TRANS. Communications, Vol. E88B, No.3 March 2005.

[136] Yusuke Sakurai and Jiro Katto, "AODV Multipath Extension using Source Route Lists with Optimized Route Establishment", International Workshop On Wireless Ad-Hoc Networks (Iwwan), 2004.

[137] Suhura Tang and Bing Zhang, "A Robust AODV Protocol with Local Update", 10th Asia-pacific Conference on Communications, IEEE, 2004.

[138] T. Chu, I. Nikolaidis, "Node density and connectivity properties of the random waypoint model", Elsevier, Computer Communications 27 (2004) 914922.

[139] Shailendra M. Tripathi and R. K. Ghosh, "An Implementational Study of Certain Heuristics for the Performance Enhancements of AODV", Proceedings of the 10th Euromicro Workshop on Parallel, Distributed and Network-based Processing (EUROMICRO-PDP'02), IEEE, 2002.

[140] S. Takahashi, J. Hakoda, H. Uehara et al., Metric selection mobile ad hoc routing protocol based on link and node costs, IEICE Technical Report, NS2003-80, RCS2003-103, July 2003.

[141] M. K. Hasan, S. Takahashi, J. I. Hakoda et al., "Route Selection Metrics inWireless Mobile Ad Hoc Networks", IEICE Trans. Fundamentals, Vol. E88A, No.10, October 2005.

[142] R. Gonner, D. Schatzmann, B. Plattner et al., "Evaluation of Scheduling Methods over Multipath Routing in WirelessMobile Ad Hoc Networks", Semester Thesis, Inistitute for Technology, Zurich, Germany, SA-2006-26.

Appendix A

Executing the Simulations

A.1 Simulator commands

The simulations are executed in the experiments of this thesis by applying a set of commands in one batch file for the simulation of each protocol. For example, the batch file "DSR.sh" contains the following nine commands:

- /root/Desktop/ns2.26/ns-allinone-2.26/ns-2.26/indep-utils/cmu-scen-gen/setdest/setdest -n 100 -p 0.0 -s 20.0 -t 250.0 -x 500 -y 500 > scen_100_0_20_250_500
- echo "scene is created...."
- ns /root/Desktop/ns2.26/ns-allinone-2.26/ns-2.26/indep-utils/cmu-scen-gen/cbrgen.tcl -type cbr -nn 100 -seed 1.0 -mc 10 -rate 10.0 > cbr_100_10_10
- echo " cbr is created...."
- ns adhoc.tcl protocol cbr_100_10_10 scen_100_0_20_250_500
- javac parsertrace.java
- echo " Java compiling finished ... "
- Java parsertrace
- echo "simulation finished....................."

Command (A.1) represents the traffic scenario generator script used to configure traffic models of the simulations using NS2 [72]:

ns cbrgen.tcl [-type cbr—tcp] [-nn nodes] [-seed seed] [-mc connections][-rate rate] > *[outdir/traffic_file]* (A.1)

Where *nn* is a number of nodes, *seed* is a random floating point number between zero and one [71][75], *mc* is a number of connections, *rate* is a transmission rate of a packet sent by a source node, and finally outdir/traffic_file is the file in which the generated scenario of traffic is saved.

The value of *seed* is used to initialize the pseudo-random number generator of a simulation. Using a fixed *seed* value produces exactly the same sequence of random numbers in all simulations. If *seed* = 0, a new seed for every simulation run is produced [74]. For all simulations of this thesis, *seed* value is fixed at 1 because the same circumstances are needed to be applied in order to perform more accurate evaluations for the routing protocols under study.

Command (A.2) represents the node movement generator script used to configure the mobility models of the simulations using NS2 [73]:

./setdest [-n no_of_nodes] [-p pausetime] [-s maxspeed] [-t simtime] [-x maxx] [-y maxy] > [outdir/movement_file] (A.2)

Where n is a number of nodes, p is a pause time, s is a maximum speed of the moving node, t is a simulation time, x and y are the maximum positions of x and y of the simulation area, and finally outdir/movement_file is the file in which the generated scenario of node mobility is saved. The sign of ">" in the command denotes to the direction of the data moving between the system and the file. In this case the file is an output file and the date is written into the file.

The nine commands mentioned above can be explained briefly as follows:

- The first command concerns generating the mobility models of the simulation based on Command (A.2). The command means that the following scenario of node movement will be generated; number of nodes is 100, pause time is 0s (highest mobility), maximum speed of a moving node is 20m/s, simulation time is 250s, and the maximum x and y positions of the simulation area are 500m and 500m respectively.

- The second command displays a confirmation message of generating the CBR traffic scene based on Command (A.1), the scene is then saved in the output file "scen_100_0_20_250_500" which is in turn used as an input file for the compiling process in the fifth command. The command mains that the following traffic scenario will be generated; traffic source type is CBR, number of nodes is 100, *seed* is 1, number of connections is 10, and packet transmission rate is 10Kbps.

- The third command concerns path setting of traffic models scenario file.

- The fourth command displays a confirmation message of creating the scenario of the selected traffic models and saving it in the output file "cbr_100_10_10" which is in turn used as an input file for the compiling process in the fifth command.

- The fifth command concerns the compiling process of "adhoc.tcl" file [79] with three parameters; the file name, the routing protocol (e.g., DSR), the input file "scen_100_0_20_250_500", and the input file "cbr_100_10_10". Two output files are produced by the compiling process, "protocol_out.tr" and "protocol_out.nam". The first file is used as an input file for the parsing process in the sixth command while the second is used for visualising the simulation.

- The sixth, seventh, and eighth commands concern compiling and executing of the parsing process of the file "parsertrace.java" [79] using Java compiler. The input file of this process is "protocol_out.tr" and the output file is "protocol_out.txt" which represents the results statistics of the simulation process of the protocol in terms of the four performance metrics mentioned earlier in Chapter 3.

- The ninth command confirms the end of the simulation process.

For the three traditional protocols, the simulation process is carried out using three batch files; "DSR.sh", "AODV.sh", and "TORA.sh". The implementations of the protocols are available in both .cc and .h files under the corresponding directory of each protocol in the main directory *ns/* of NS2 installed package.

To visualise the simulations, a visualisation process is performed using NAM (Network Animator) on the nam file associated with each protocol simulation. Figure A.1, Figure A.2, and Figure A.3 show snapshots of three NAM windows for the simulation processes of DSR, AODV, and TORA protocols as examples of using the above scenarios. DSR simulation looks like AODV while TORA is different due to the difference in its mechanism. Each circle shown in Figure A.3 represents an area of small set of nodes near the potential change of topology. Each node in this set of nodes maintains routing information about the first hop neighbours.

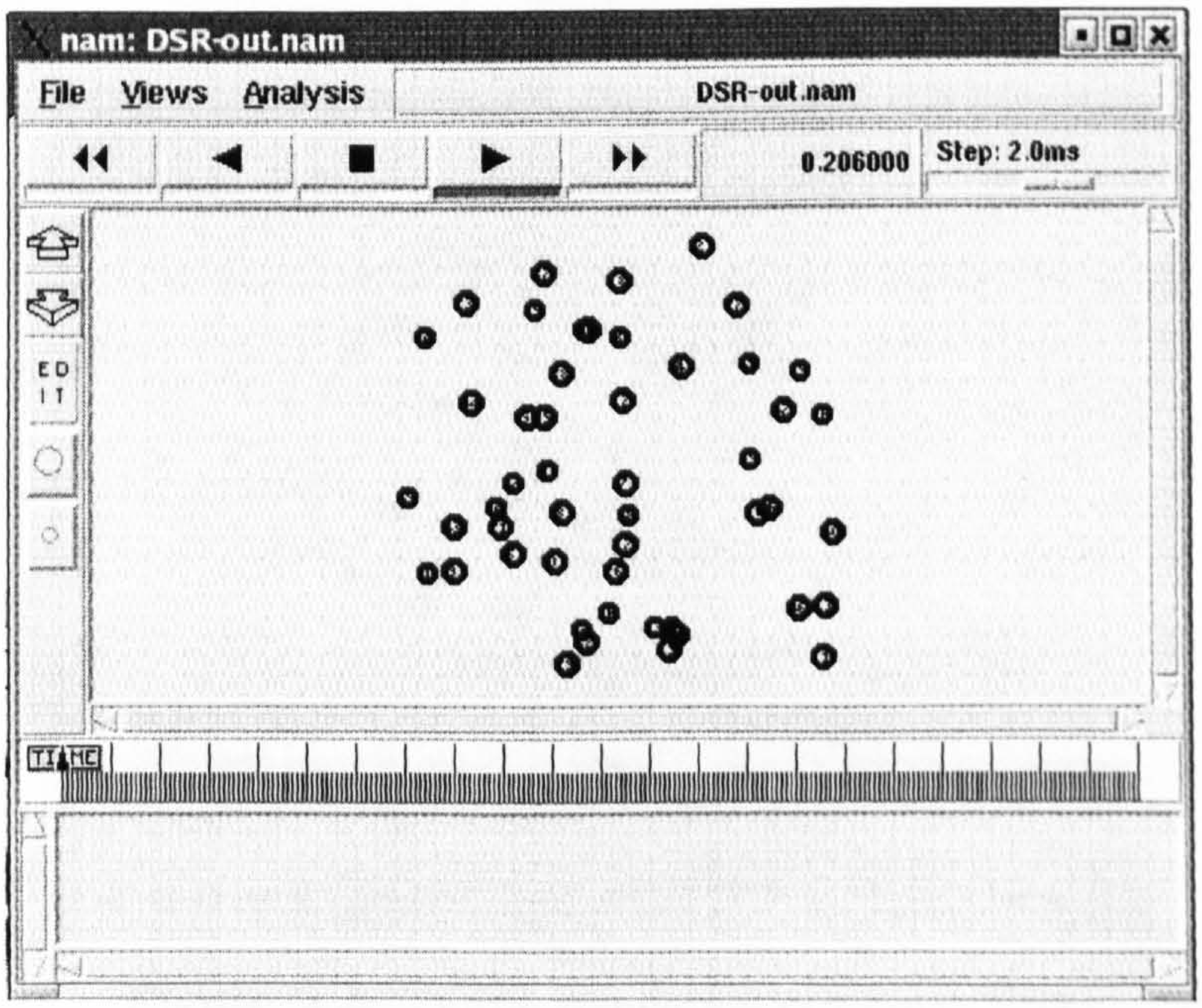

Figure A.1: DSR simulation process in NS2

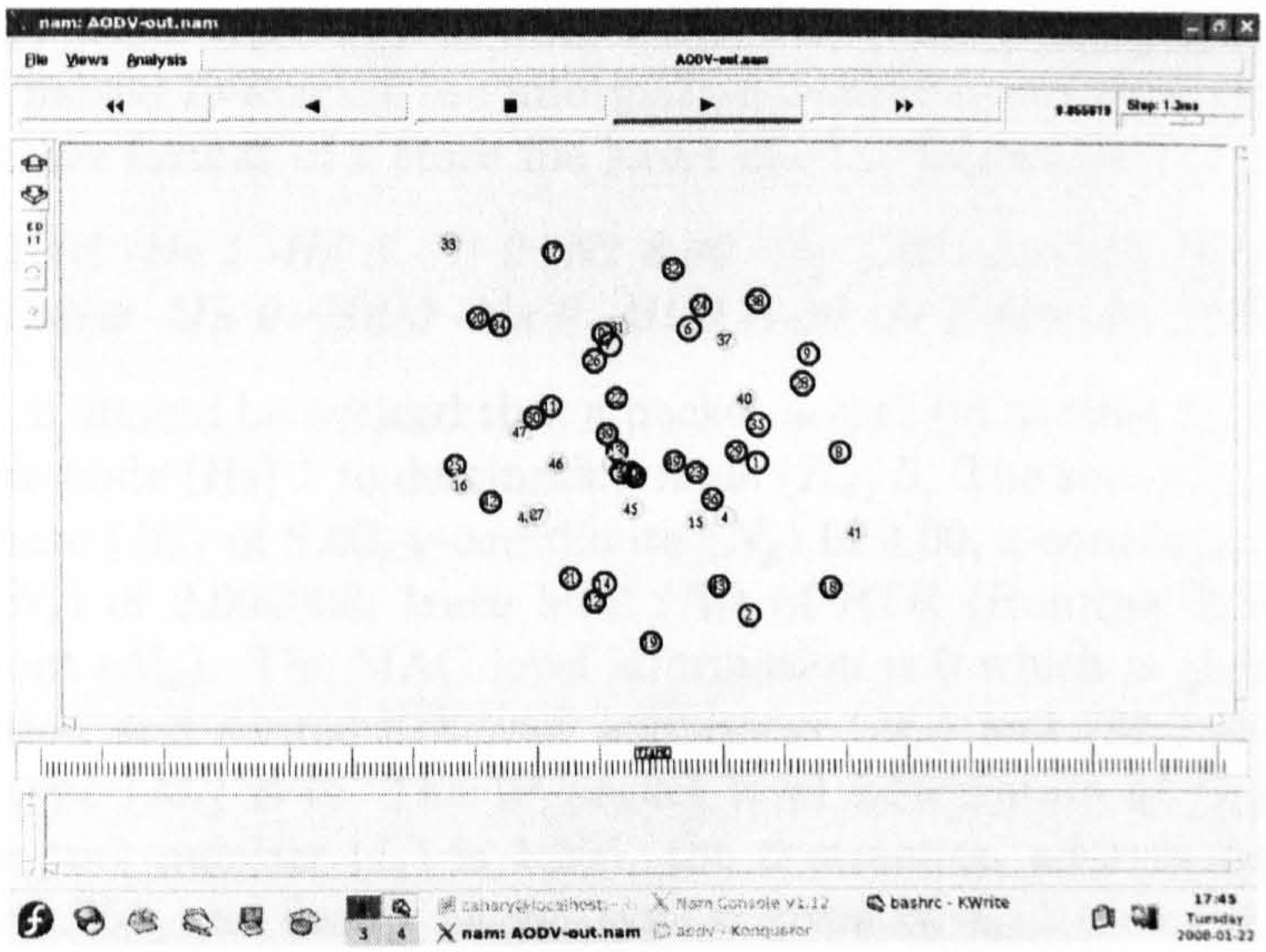

Figure A.2: AODV simulation process in NS2

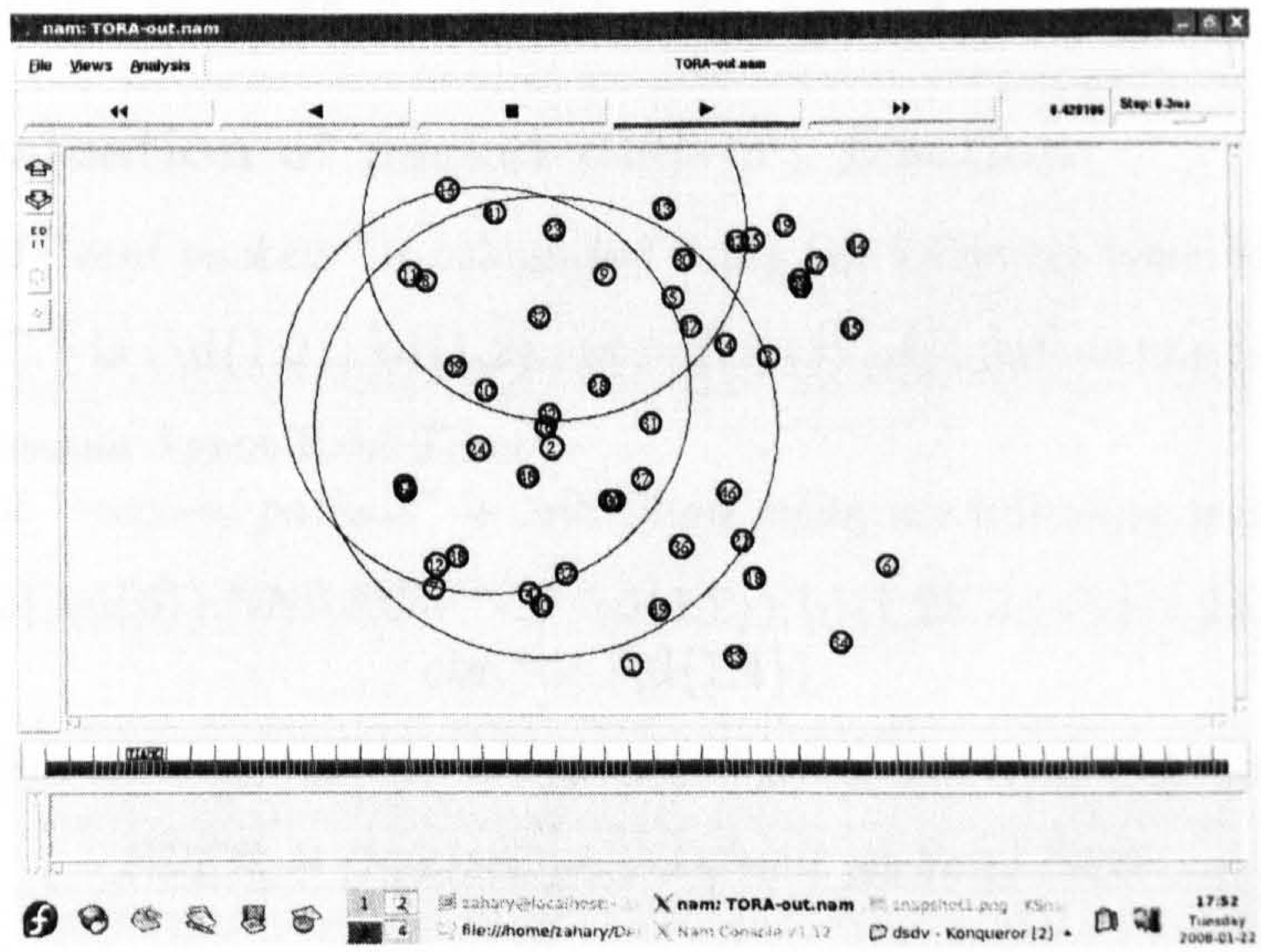

Figure A.3: TORA simulation process in NS2

A.2 Parsing the simulation trace files

After each simulation, trace files of both traffic and node movements are generated. Trace files are parsed to extract the information needed to measure the performance metrics. The trace format of a trace file looks like the following:

s -t 0.320645992 -Hs 1 -Hd 5 -Ni 0 -Nx 8.00 -Ny 4.00 -Nz 0.00 Ne 2.000000 -Nl RTR -Nw -Ma 0 -Md 0 -Ms 0 -Mt 0 Ii 20 -Is 1.255 -Id 5.255 -It

In this format, it should be noticed that a packet is sent (s) at time (t) = 0.320645992 sec, from source node (Hs) 1 to destination node (H_d) 5. The source node id (N_i) is 0 with x-coordinate (N_x) of 8.00, y-coordinate (N_y) Of 4.00, z-coordinate (N_z) of 0.00, energy level (N_e) of 2.000000, trace level (N_l) of RTR (Routing Trace level), and blank node event (N_w). The MAC level information is 0 which is given by duration (M_a), destination and source Ethernet addressess (M_d) and (M_s) are both 0, and the Ethernet type (M_t) is 0. The IP packet level information id (I_i) is 20, source address.source port number (I_s) is 1.255, the destination address.destination port number (I_d) is 5.255, and finally packet type is given by I_t.

A.2.1 Important note regarding the parsing process

In order to avoid the randomisation in the results, three simulations are carried out for each mobility scenario and consequently three trace files (.tr) are produced for each protocol. each trace file is parsed and the average results of each performance metric are recorded as shown in Tables 3.1, 3.2, 3.3, and 3.4.

A.2.2 Evaluation of packet delivery fraction

The number of *"sent packets"* is calculated using the following trace form:

/^s *- Nl AGT.*-Is (\d{1,2}).\d{1,2} -Id (\d{1,2}).\d{1,2}.*-It cbr.*-Ii (\d{1,4})/

Where *AGT* means Agent-level Trace.
The number of *"received packets"* is calculated using the following trace form:

/^r -t (\d{1,2}.\d{6}).*-Nl\AGT.*-Is (\d{1,2}).\d{1,2} -Id (\d{1,2}).\d{1,2}.*-It cbr.*-Ii (\d{1,4})/

Then, the packet delivery fraction is calculated using the following formula:

*PDF% = (received packets/sent packets) *100*

A.2.3 Evaluation of average end-to-end delay

For each packet with $id(I_i)$ of trace level AGT and type CBR, sending time t_s, receiving time t_r, and average i_t are finally calculated.

A.2.4 Evaluation of normalised routing load

Evaluating normalised routing load (routing packets overhead) is accomplished by calculating the number of routing packets sent depending on the following format:

/^[s|f].*-Nl RTR.*-It (?:AODV|message) -Il (\d{1,2})/

Where *f* denotes to forward while *RTR* denotes to Routing Trace level, AODV is an example of the protocol used.
Then, the normalised routing load is calculated using the following formula:

Normalised routing load = routing packets sent/received

A.2.5 Evaluation of throughput

Evaluating throughput is performed by calculating only the number of *"sent packets"* using the same trace form mentioned above for packet delivery fraction evaluation. Calculating the number of *"received packets"* is not required for throughput.